

CALIFORNIA'S FIFTH
CLIMATE CHANGE
ASSESSMENT

Sierra Nevada Regional Report

A Regional Report for California's Fifth Climate Change Assessment

Coordinating Agency

CA Governor's Office of
Land Use and
Climate Innovation

About California's Fifth Climate Change Assessment

California's Climate Change Assessments are the state's scientific foundation for understanding future climate-related vulnerability across California's regions and systems. Senate Bill 1320 (Stern, 2020) requires the State to report the impacts and risks of climate change across California at least every five years, beginning with California's Fifth Climate Change Assessment (Fifth Assessment). Building on decades of climate research and previous Assessments, the Fifth Assessment presents new findings about California's climate future, with a dedicated focus on Tribal partnerships, public engagement, and communities most vulnerable to climate impacts.

The Fifth Assessment's research and tools are designed to fill knowledge gaps about California's climate future, inspire strategic climate actions, and shape planning, investments, and policies at the state, regional, and local scales. Guided by research priorities identified by state, Tribal, and local leaders, community representatives, and subject matter experts, its findings are designed to help illuminate potential climate futures, the challenges they may present, and the opportunities to build resilience through adaptation pathways.

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

Purpose of the Regional Reports

The Fifth Assessment Regional Reports bring together the latest climate science, community input, and adaptation opportunities to meet the needs of communities across nine California regions. These reports can inform regional and local vulnerability assessments, adaptation planning, and community resilience efforts. The Regional Reports include analyses of climate projections and impacts to natural systems, built systems, and social systems. They uplift case studies of adaptation solutions and highlight developments that have emerged since the Fourth Assessment was released in 2018. While climate impacts are felt across regional boundaries, the Regional Reports deepen our understanding of how climate change interacts with the unique communities, histories, waters, and landscapes across California.

Climate Modeling, Scenarios, & Time Periods

The Fifth Assessment Regional Reports consider the following climate models, greenhouse gas (GHG) emissions scenarios, and time periods:

- **CMIP6** (Coupled Model Intercomparison Project Phase 6) is the most recent version of a global collaboration that standardizes and combines the most advanced climate models to project how Earth's systems will react to our changing atmosphere. With CMIP6, we can see the most likely climate trends and the less likely, but still possible, extremes.
- **Greenhouse Gas Emissions Scenarios:** Current international climate models integrate two kinds of scenarios: Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs). The SSPs model how global society might evolve over the next century, including changes in population, policy, technology, and economic growth, while tracking the amount of heat trapped in the atmosphere. The RCPs correspond to GHG emissions and capture a quantifiable range of emissions and warming—how much do we expect the world will continue to emit, and the associated warming, throughout the century? Combined, these describe how global social conditions (e.g., population, technological, and economic growth) affect emission trajectories. This shift offers a more nuanced understanding of how our collective decisions today will shape the climate of tomorrow. The Fifth Assessment research primarily focuses on two RCP/SSP combinations:
- **SSP 2–4.5** (i.e., utilizing the second SSP narrative and RCP 4.5) describes an intermediate scenario indicating improvements toward meeting mitigation commitments. This scenario shows carbon dioxide equivalent (CO2e) emissions initially hover at current levels, then start to fall by mid-century.
- **SSP 3–7.0** articulates a high emissions scenario and less optimistic pathway, assuming current emission levels continue throughout the year 2100. This scenario shows CO2e emissions doubling by 2100.
- The Fifth Assessment also references a more aggressive emissions scenario (**SSP5-8.5**), which describes a very high and unlikely emissions pathway that shows CO2e emissions tripling by 2075. The Assessment includes this scenario as a reference tool for a worst-case emissions outcome for informational and planning purposes rather than a plausible climate change future.
- **Global Warming Levels** (GWLs) ask "What happens to California once the world reaches a certain level of warming?" The focus is on adapting to a change in the expected climate, such as a 2°C (3.6°F) increase. While these models identify a range of years when these thresholds might be reached, the emphasis is on the intensity of the impact rather than the calendar date. This is a different and complementary approach to the previously used *date-based approach*.
- **Downscaling with Localized Constructed Analogues (LOCA) and Weather Research and Forecasting (WRF):** To make global climate models (GCMs) useful for local planning, scientists use a technique called downscaling. While global models provide a *big picture* view of the planet, the Fifth Assessment uses the LOCA2 statistical and WRF dynamical downscaling techniques and a hybridized version of these techniques, LOCA2-Hybrid, to focus on California's particular climate future.
- **Time Periods:** The Fifth Assessment uses a 30-year timeframe for analyses, as shown in the table below, alongside historical projections to draw comparisons between current and future time periods.

Descriptive Term	Time Range
Historical	1981–2010
Mid-Century	2041–2070
Late-Century	2071–2100

CALIFORNIA'S FIFTH
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Map of California

Climate Change Assessment Regions

Authors and Contributors

Coordinating Lead Author

Safeeq Khan, *University of California, Merced*

Lead Authors

Tapan Pathak
University of California Agriculture and Natural Resources

Kaeleigh Reynolds
Sierra Business Council

Contributing Authors

Leander Anderegg
University of California, Santa Barbara

Logan Bremer-Kelly
Sierra Business Council

Sarah Campe
Sierra Nevada Conservancy

Brent Campos
Point Blue

Abhishek Chakraborty
University of California, Merced

Laurie Huning
California State University, Long Beach

Prakash Jha
University of California Agriculture and Natural Resources

Cody Reed
Point Blue

Anna Trugman
University of California, Santa Barbara

Alyssa Whitaker
California Department of Water Resources

Aaron Wilcher
University of California Agriculture and Natural Resources

Technical Advisors

Christy Brigham
The Nature Conservancy

Adrian Das
United States Geological Survey

Mike Dettinger
United States Geological Survey (retired)

Thomas Harmon
University of California, Merced

Patricia N. Manley
United States Forest Service

Community Advisors

John Wentworth
Mammoth Lakes Trails and Public Access Foundation

Jenny Hatch
Sierra Nevada Alliance

Liesbet Olaerts
Sierra Nevada Alliance

Tribal Advisors

Dean Tonenna
Mono Lake Kootzaduka'a Tribe

Raymond Gutteriez
Wuksachi Indian Tribe

Christina McDonald
North Fork Rancheria of Mono Indians

Brian Wallace
Washoe and Nisenan

Associate Editor

David Herbst
University of California, Santa Barbara

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Any references in this Assessment to the lingering and compounding effects of racism and discrimination are drawn from academic literature and are not factual findings of, or legal determinations by, the State of California or any agencies of the State, of prohibited discrimination in any particular instance. Similarly, any descriptions of potential future harms are not findings of or admissions by the State of California or any agencies of the State.

The research was reviewed by expert reviewers, Tribal Advisory Group members, and approved by an external editorial board to ensure scientific rigor as well as appropriate representation of the practitioners and partners to whom each report applies.

Use of Artificial Intelligence (AI):

The authors did not use generative AI to create original content in the preparation of this report. However, we acknowledge the use of assistive AI as well as AI-enhanced search engines during the literature review, improving sentence clarity, and bibliographic formatting. In these cases, the resulting content was validated by the authors. Thus, authors take full responsibility for the correctness of the contents of this report.

Executive Summary

The Sierra Nevada region of California is a natural wonder and biodiversity hotspot, playing a critical role in regulating the state's environment and economy. A majority of this region is publicly owned and covered by coniferous forests, shrublands, and grasslands. Its diverse topography and elevation gradients create a climate characterized by cool, wet winters and warm, dry summers, with considerable variability across the region. A sharp contrast exists between western and eastern slopes of the Sierra Nevada range with the latter being drier, caused by the rain shadow effect, and more rugged because of steeper slopes. In terms of temporal variability, the Sierra Nevada region experiences some of the largest year-to-year climate variability in the United States.

Climate change is already affecting the Sierra Nevada, with rising temperatures, shifting precipitation patterns, and declining snowpacks. By the end of the 21st century (2071–2100), model predictions indicate that the average daily maximum temperatures (T_{max}) in the Sierra Nevada are expected to increase by 5.65±0.24°F under Shared Socioeconomic Pathways (SSPs) 2–4.5 and as much as 9.32±0.39°F under SSP 5–8.5, with intermediate warming under SSP 3–7.0. Corresponding minimum temperatures (T_{min}) are expected to increase by 5.30±0.29°F and 9.13±0.36°F under SSP 2–4.5 and SSP 5–8.5, respectively. These warming trends are consistent across all climate models, indicating a very likely outcome and very high confidence. While long-term changes in end-century (2071–2100) total precipitation are expected to show average modest increase throughout the region with a larger uncertainty, generally within 3.0±7.0% to 5.0±12.0% depending on the SSPs, a significant variability in the intensity, frequency, and timing of precipitation is likely. These changes are expected to drive more frequent and severe droughts, stronger winter storms, and other hazards associated with extreme precipitation events (e.g., flooding, landslides, power supply disruptions, and damage to roads and bridges).

The projected warming is enough to raise the rain-snow transition by 1,500–3,000 feet, dramatically reducing snowpack across the range. Snowpack is projected to decline under all emission scenarios, with a strong agreement among models. By mid-century (2041–2070), April 1 snow water equivalent (SWE) reductions of 47±12% (SSP 2–4.5) and 60±14% (SSP 5–8.5) are projected, intensifying by end-century (2071–2100) to 67±16% and 84±12% under *intermediate* and *worst-case* scenarios. The snowpack decline is expected to alter the magnitude and timing of streamflow, worsening summer dryness, reducing groundwater recharge, and stressing both local and statewide water systems, aquatic and terrestrial ecosystems, and communities. For species that have specific physical or phenological adaptations to snowpack, reduced snowpack is a key stressor and a form of habitat loss. Continued decline in mountain snowpack is inevitable, but extreme climate swings or weather whiplash will likely continue to unleash bursts of snow, swinging from little-to-no snow in one year to record-setting conditions in another. Extreme precipitation events, often associated with atmospheric rivers, are also projected to intensify, increasing the risks of flood, erosion and sedimentation, and post-fire debris flow. These extreme hydrologic conditions will increasingly challenge ecosystems and built systems alike, especially reservoir operations caught between the opposing objectives of flood control and water storage.

Over the past several decades, forest ecosystems in the Sierra Nevada have shown a strong vulnerability to a range of threats, from drought to wildfire and insect infestation. Climate change is shifting much of the Sierra's forested area toward a climate space typically associated with shrublands, grasslands, or deserts. More frequent and intense droughts and fires are causing abrupt changes in forest ecosystem structure and ecosystem services or, in some cases, a complete type conversion (e.g., from forest to shrubland). Woodlands are experiencing a similar shift with many oak species experiencing mortality, lack of recruitment, range shift, and type conversion. Overall impacts on shrublands are less clear with some evidence of shrubs being climate beneficiaries, especially in fire-prone and alpine regions.

The Sierra Nevada region is home to 1.2 million residents and more than 70 Native American Tribes, including but not limited to the Mono, Miwok, Paiute, Washoe, Yokuts, and Tübatulabal peoples. The hydroclimatic shifts and cascading impacts on water and ecosystem discussed earlier poses significant risks that threaten local communities and economies. Rural populations dependent on natural resource- and recreation-based industries are particularly vulnerable to extreme heat, shifting precipitation patterns, flooding, and increasingly destructive wildfires. More than one-third of the region falls within California Department of Forestry and Fire Protection's (CAL FIRE's) high or very high wildfire hazard zones, and most incorporated towns face very high hazard levels in their local responsibility areas. These hazards endanger essential infrastructure, public health, and livelihoods while straining already limited emergency services and financial resources. The Sierra Nevada region provides the state with critical ecosystem services—including supplying over 60% of the state's developed water, storing carbon in forests and meadows, and supporting winter recreation—valued between $43.6 and $190.9 billion annually in some subregions. Yet, socioeconomic conditions compound climate vulnerability: at least 40% of households live in counties with a median income below the state's median of $91,551, and many communities have high proportions of older adults, residents with disabilities, or people living in poverty.

Wildfires remain the most acute threat to communities, with the record-breaking 2020 and 2021 fire seasons costing billions of dollars in damages, displacing communities, and contributing to insurance market instability. Nine of the ten California counties with the highest exposure to wildfire are in the Sierra Nevada region. Vulnerable groups, including nearly 550,000 residents living in poverty and over 445,000 people with disabilities across the region, bear disproportionate risks to safety, health, and recovery.

Multiple efforts are underway to help the region adapt to the new realities of a warmer and drier future. Water and other utilities are investing in data-driven water and infrastructure management. Land and ecosystem managers are investing in multi-benefit collaborative forest and meadow restoration, strengthening partnerships with Tribes, investing in Indigenous stewardship, and leveraging innovative financing. State investments in expanded workforce training programs and building fire and forest resilience and economic diversification further highlight pathways toward climate mitigation and adaptation. These efforts underscore the urgency of advancing region-specific, community-driven strategies that align resilience, equity, and sustainable economic development in the Sierra Nevada.

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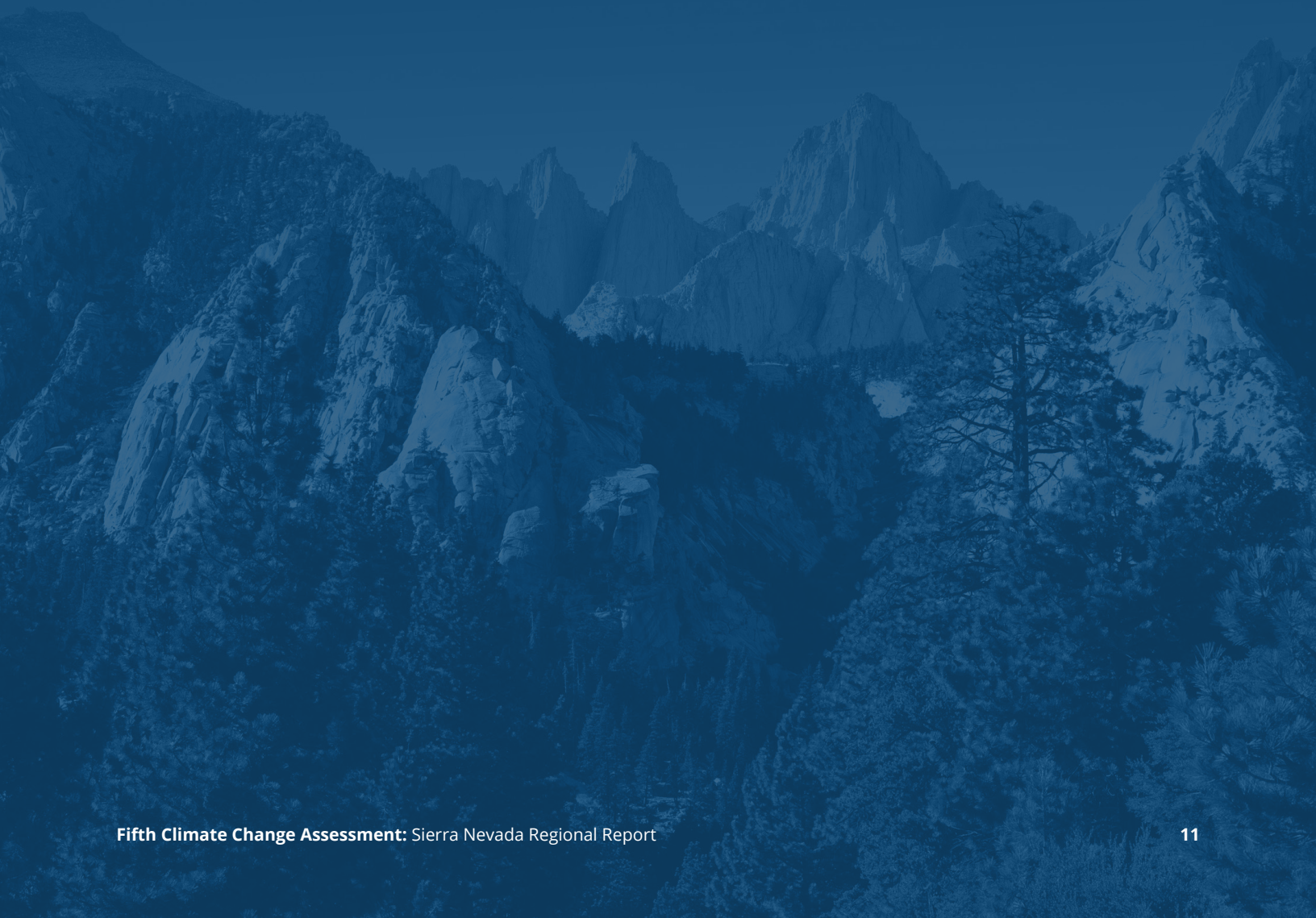
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Chapter 1.

Introduction



The Sierra Nevada is a major mountain range in eastern California, extending approximately 400 miles north to south and spanning about 70 miles east to west with a total area of roughly 25,000 square miles (**Figure 1.1**). Elevation increases from the western foothills around 1,600 feet to the summit of Mount Whitney at 14,505 feet, the highest point in the contiguous United States. The highest elevations are found in the southern range and gradually decrease from south to north. The region also includes notable subranges such as the Warner, White, and Inyo Mountains, and extends toward adjacent desert basins.

The Sierra Nevada is the ancestral and contemporary homeland of many Tribes and Tribal communities, including but not limited to the Mono, Miwuk, Paiute, Washoe, Yokuts, and Tübatulabal peoples, as well as federally recognized and non-federally recognized Tribal Nations such as the Big Sandy Rancheria Band of Western Mono Indians, North Fork Rancheria of Mono Indians, Table Mountain Rancheria, Tule River Tribe, Tejon Indian Tribe, Big Pine Band of Owens Valley Paiute Shoshone Indians, and the Washoe Tribe of Nevada and California, among others. This acknowledgment is not intended to be exhaustive, and the report respectfully recognizes that additional Tribes and Indigenous communities maintain historical, cultural, and ongoing connections to this region (National Park Service, n.d.). The stewardship practices from the Indigenous Peoples and Tribal communities have shaped the region's ecological resilience long before and after colonization (Anderson, 2005; SNC, n.d.).

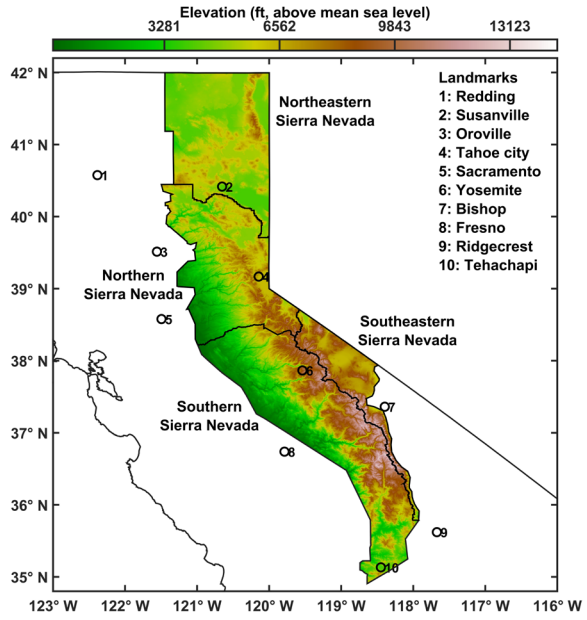


Figure 1.1: *Elevation across the Sierra Nevada, subregions, and some landmarks.*

Approximately 90% of the Sierra Nevada region (**Figure 1.1**) is covered by forests, shrublands, and grasslands, while less than 3% of the area is cultivated for agriculture and used for urban development. Vegetation composition varies notably across the four sub-regions. Coniferous forests dominate both the Northern and Southern Sierra Nevada subregions, whereas steppe shrublands are the most prevalent in the Northeastern and Southeastern Sierra Nevada. For example, coniferous forests cover about 60% of the Northern Sierra Nevada but only 11% of the Northeastern and Southeastern Sierra Nevada. Desert scrub and sagebrush account for approximately 76% of the landscape in Northeastern and Southeastern Sierra Nevada (FRAP, 2017). The Sierra Nevada is predominantly composed of Mesozoic granitic intrusive rocks formed during subduction, although later volcanic activity occurred in the northern part of the range, particularly north of Yosemite (YFS, n.d.).

The region's land use is diverse, comprising protected national parks, national forests, designated wilderness and monuments, timber production, livestock grazing, hydropower generation, recreation, and limited agriculture. Although it is sparsely populated compared to California's

urban centers, about 1.2 million people call this region home, including over 70 Native American Tribes scattered among rural towns and small cities. About 67% of the Sierra Nevada region is publicly owned, which includes ten national forests (Modoc, Lassen, Plumas, Tahoe, El Dorado, Stanislaus, Sierra, Sequoia, Inyo, and western part of Humboldt-Toiyabe National Forests), three national parks (Yosemite, Sequoia-Kings Canyon, and Lassen Volcanic), and Devils Postpile National Monument.

Beyond its ecological and cultural importance, the Sierra Nevada plays a critical role in California's hydrological system. It provides an estimated 26 million acre-feet (MAF) of streamflow annually to the Central Valley, and an additional 2 MAF flowing into the rain-shadow desert valleys to the east (Dettinger et al., 2018). The region supports a vast hydropower network, with Pacific Gas and Electric Company (PG&E) alone generating approximately 3,900 megawatts of electricity to nearly four million homes (PG&E, 2024), accounting for about one-third of the state's hydroelectric capacity. Mountain block recharge from the Sierra Nevada contributes approximately 31–53% of the total groundwater recharge to the Central Valley aquifer, highlighting a stronger mountain-valley hydrologic connection (Armengol et al., 2024). This subsurface inflow delivers an average of 4 MAF of water annually—accounting for about 10% of all water inputs to the Central Valley aquifer from both surface and subsurface sources (Argus et al., 2022). The region also functions as the state's *natural reservoir*, as its snowpack stores approximately 15 MAF of water, equivalent to about 61–71% of the long-term average reservoir storage (Margulis et al., 2016; Dettinger & Anderson, 2015; Bales et al., 2011). This snowmelt sustains rivers, reservoirs, aquatic life, and water systems during the prolonged summer dry period. Much of the state's infrastructure is designed around this seasonal snowmelt, which accounts for about 73% of the total annual average runoff (Li et al., 2017) and 42% of California's annual water movement (Dettinger et al., 2018).

Sierra Nevada's environmental and socio-economic diversity makes it both vulnerable and resilient in the face of climate change. Years of water infrastructure development, land use and wildfire suppression policies, and criminalization of Indigenous land stewardship practices have severely impacted the flora and fauna of the region (e.g., 1850 Act for the Government and Protection of Indians [Johnston-Dodds, 2002]; Executive Order N-15-19: Newsom's Apology to Tribes [Office of the Governor of California, 2019]). Through this report, we recognize and honor the enduring role of Indigenous Peoples and Tribal communities in sustaining the environmental and cultural heritage of the Sierra Nevada. This report aims to provide decision-makers, planners, and communities with accessible information to guide adaptation efforts. It also seeks to promote broader public engagement and share California's approach to climate adaptation and resilience with national and international partners. Subsequent sections will present climate projections for the 21st century, followed by analyses of key vulnerabilities, adaptation strategies, and opportunities for the region's natural working lands and waters, built systems, and social systems.

Administratively, this assessment divides the Sierra Nevada region into four subregions (**Figure 1.1**): (1) Northeastern Sierra Nevada, which includes Lassen and Modoc counties in the northeast; (2) Northern Sierra Nevada, covering Plumas, Sierra, Nevada, Placer, El Dorado, Alpine, and Amador counties; (3) Southeastern Sierra Nevada, covering parts of Mono and Inyo counties; and (4) Southern Sierra Nevada, which includes Calaveras, Tuolumne, Mariposa, and eastern parts of Madera, Fresno, Tulare, and Kern counties. We also summarize key trends at smaller scales, eight-digit Hydrologic Unit Codes or HUC-8, for local climate and watershed stewards, land and water managers, and practitioners.

Chapter 2.

Climate Science: Historical & Projected Trends



Key Message

The Sierra Nevada region is experiencing rapid changes in climate, including in temperature, precipitation, snowpack, and hydrologic regimes, with cascading consequences and compounding hazards for water resources, ecosystems, built systems, and communities. Rising temperatures are evident across all models and timescales, resulting in expected snowpack loss, earlier snowmelt, and a shift from snow to rain. The long-term changes in precipitation remain relatively modest, however, extreme precipitation events, often associated with atmospheric rivers, are projected to increase. At the same time, the region is also projected to experience more frequent and prolonged dry periods, in addition to the changes in runoff timing, reduced summer streamflow, dry soil, and increased evaporative demand that the region is already experiencing. Future projected changes are likely to put more stress on forests, water infrastructure, and downstream users, highlighting the need for forward-looking climate adaptation strategies for the Sierra Nevada.

2.1 Historical Climate

The Sierra Nevada region experiences a predominantly Mediterranean climate, characterized by cool, wet winters and warm, dry summers (Polade et al., 2017; Dettinger et al., 2016). However, its complex topography results in substantial climatic variability across the range. The Southern Sierra Nevada is generally higher in elevation and therefore cooler, resulting in a larger fraction of precipitation falling as snow. In contrast, the Northern Sierra Nevada, with relatively lower elevations, is wetter due to a large fraction of precipitation falling as rain instead of snow and because of its greater exposure to North Pacific storm tracks, including atmospheric rivers that increasingly deliver intense precipitation at landfall (Rutz et al., 2014). The western slopes receive most of their precipitation from prevailing westerlies originating over the Pacific Ocean. Conversely, the eastern slopes, being in the rain shadow, receive much less precipitation, primarily from spillover events and occasional Great Basin systems, such as inside sliders and the North American monsoon (Dettinger et al., 2018).

Precipitation in the Sierra Nevada is largely dependent on atmospheric river storms, which accounts for 30–50% of the annual precipitation in the West Coast states (NOAA, 2025). Seasonal snowpack in the region accumulates over relatively few days and snowstorms (Huning & Margulis, 2017; Serreze et al., 2001). In the Sierra Nevada specifically, atmospheric river events contribute over 40% of the seasonal snowpack (Shulgina et al., 2023). Precipitation is amplified as moist air ascends the Sierra's western slopes, resulting in some of the highest totals at mid-elevations (5,000–6,000 feet) (Huning & Margulis, 2018; Lundquist et al., 2010, 2015 Dettinger et al., 2004).

The Sierra Nevada experiences pronounced spatial and temporal variability in precipitation. Historically, annual precipitation has fluctuated between 50–200% of the long-term average, far exceeding the 10–20% variability typical in much of the continental United States (Dettinger et al., 2011). This high year-to-year variability is largely driven by the number and intensity of winter storms reaching the region. Because these storms can vary in both strength and path, they often affect parts of the Sierra Nevada differently, leading to significant spatial differences in precipitation (**Figure 2.1**). For example, during the 2012–2016 drought, the western foothills received nearly half a year's worth more in precipitation than higher elevations.

Temperature fluctuations are also large, though generally less extreme than those in interior regions of the United States due to the moderating influence of the Pacific Ocean (**Figure 2.1**). The Pacific Ocean not only buffers seasonal and interannual temperature variations but also plays a central role in shaping sub-seasonal to decadal climate variability through large-scale ocean-atmosphere phenomena such as the El Niño–Southern Oscillation (ENSO) (Lee et al., 2018).

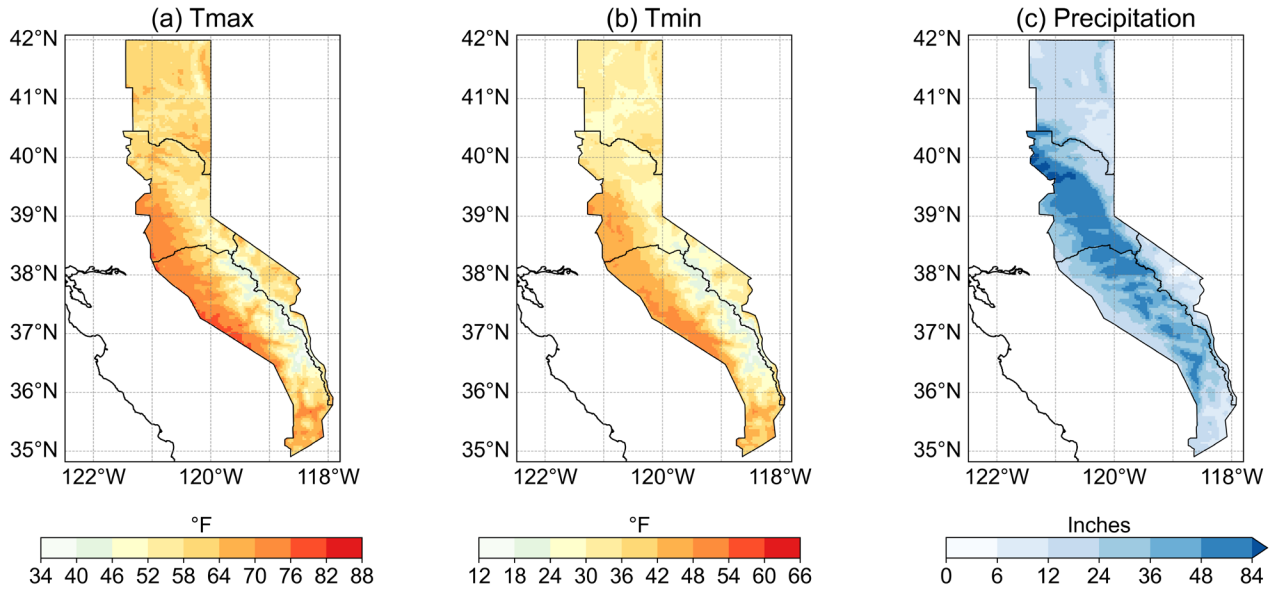


Figure 2.1: *Maps of historical baseline (1981–2010) annual average (a) maximum daily temperature (T_{max}), (b) minimum daily temperature (T_{min}), and (c) precipitation (reported as liquid water equivalent), respectively.*

Seasonal snow accumulation increases along a southward gradient, driven primarily by temperature (Bales et al., 2011). Despite higher latitudes, much of the Northern Sierra Nevada receives snow near freezing temperatures due to lower elevation, making them highly sensitive to temperature fluctuations during the winter rainy season (Safeeq et al., 2015). This makes the snowpack in the Northern Sierra Nevada more vulnerable to warming than those in the southern portion of the mountain range that sits at higher altitude (Huning & AghaKouchak, 2018). Historically, it has been about 20–40% more likely to have a below average snowpack for a 1–2°C (1.8–3.6 °F) of warming over the winter in the Sierra Nevada (Huning & AghaKouchak, 2018).

2.2 Temperature and Precipitation Trends

The Sierra Nevada region (**Figure 1.1**) is already showing clear signs of climate change, including long-term warming trends and altered precipitation extremes. Historical maximum temperatures (T_{max}), have been increasing at a rate of 1.4°F/century since 1895, which has increased by over three-fold (4.9°F/century) since 1981. This trend is much stronger in minimum temperatures (T_{min}), increasing at a rate of 2.7°F/century since 1895 and showing over three-fold increase in the rate of warming (8.9°F/century) since 1981. Trends in annual precipitation are downward but statistically

not significant, either over the entire record or since 1981. However, warmer temperatures are amplifying drought severity (Shukla et al., 2015) and forest water stress (Goulden & Bales, 2019). All these trends indicate more profound changes in the decades ahead. While atmospheric concentrations of greenhouse gases (GHGs) have fluctuated naturally over hundreds of thousands of years, the rapid increase since the industrial revolution is unprecedented in the paleoclimate record (IPCC, 2023; Eyring et al., 2016). GHGs, such as carbon dioxide, methane, and water vapor, act as a thermal blanket, trapping outgoing infrared radiation and warming the Earth's surface, atmosphere, and oceans, thereby driving widespread climatic shifts.

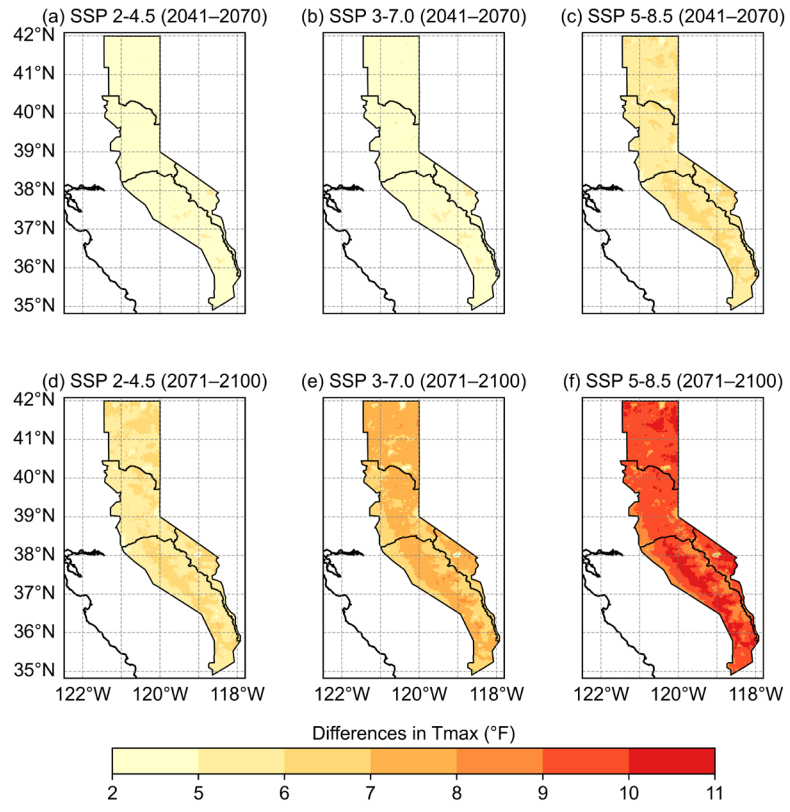


Figure 2.2: *Projected changes, relative to baseline (1981–2010), in maximum temperature (T_{max}) for 2041–2070 (a, b, c) and 2071–2100 (d, e, f), under SSP 2–4.5 (a, d), SSP 3–7.0 (b, e) and SSP 5–8.5 (c, f).*

Multiple lines of evidence from historical observations and climate model simulations confirm that several of these observed changes in the Sierra Nevada region, and other western United States mountain ranges, are consistent with human-caused climate change (Diffenbaugh et al., 2015). Since the mid-20th century, these changes include significant increases in nighttime temperatures, a declining proportion of precipitation falling as snow, reductions in spring snowpack, and earlier snowmelt and snowmelt-driven streamflow (Siirila-Woodburn et al., 2021; Mote et al., 2018; Barnett et al., 2008). These trends align with projections from models based on observed GHG emissions and are expected to intensify further in the coming decades. Additional impacts, such as shifts in precipitation patterns and extremes, reduced soil and vegetation moisture, and altered streamflow volumes and thermal regimes, are also expected to emerge more clearly as non-anthropogenic drivers of *historic variability* become less dominant. In this assessment, historic variability refers to climate and ecosystem fluctuations observed over the 1981–2010 historical baseline period. While Sierra Nevada ecosystems have been shaped by longer-term paleoclimate variability, those timescales are beyond the resolution and scope of this report.

Since the exact amounts of future GHGs emissions are uncertain, we rely on plausible emission scenarios to estimate potential future trajectories. These scenarios, called Shared Socioeconomic

Pathways (SSPs) in Coupled Model Intercomparison Project Phase 6 (CMIP6), represent a range of possible socioeconomic and policy pathways, allowing climate projections to account for varying levels of emissions and their potential impacts (Riahi et al., 2017; Eyring et al., 2016; O'Neill et al., 2016). Each SSP is associated with a specific level of stratospheric adjusted radiative forcing (measured in watts per square meter, Wm^{-2}) by the year 2100. This value indicates the additional heat trapped in the Earth's atmosphere due to GHGs under a given scenario. These SSPs are broadly comparable to the Representative Concentration Pathways (RCPs) used in previous CMIP5 experiments (Tebaldi et al., 2021).

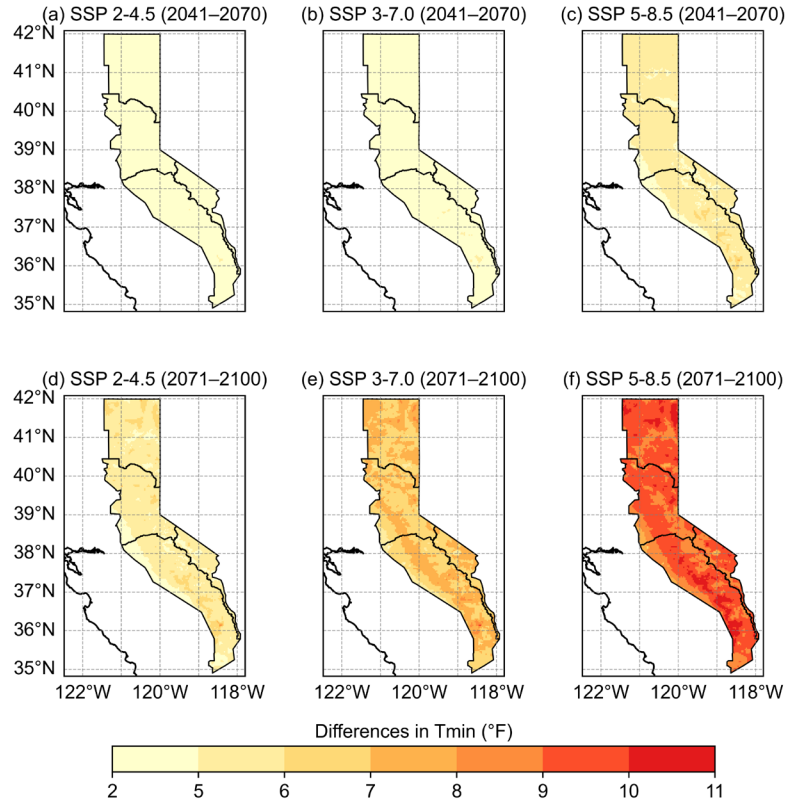


Figure 2.3: *Projected changes, relative to baseline (1981–2010), in minimum temperature (T_{min}) for 2041–2070 (a, b, c) and 2071–2100 (d, e, f), under SSP 2–4.5 (a, d), SSP 3–7.0 (b, e) and SSP 5–8.5 (c, f).*

In this report, we use climate projections based on three pathways of future GHGs emissions. SSP 2–4.5 and SSP 3–7.0 are emphasized as *intermediate* and *high* emissions scenarios, respectively, that are most relevant for near- and mid-term planning. SSP 2–4.5, assumes emissions stabilize around 2050 and then decline continually, resulting in a moderate increase in radiative forcing (4.5 Wm^{-2}) by the end of 2100. This scenario is broadly comparable to RCP 4.5 used in California's Fourth Climate Change Assessment (Fourth Assessment). SSP 3–7.0 represents a higher-emissions pathway in which emissions continue to rise throughout the 21st century, but at a slower rate than those in SSP 5–8.5. SSP 5–8.5, the highest emissions pathway, assumes emissions continue to rise unabated through 2100, causing greater increase in radiative forcing (8.5 Wm^{-2}), roughly corresponding to RCP 8.5 used in the Fourth Assessment. It is included here as a *worst-case* scenario to bound uncertainty and inform the most aggressive adaptation and risk-management planning.

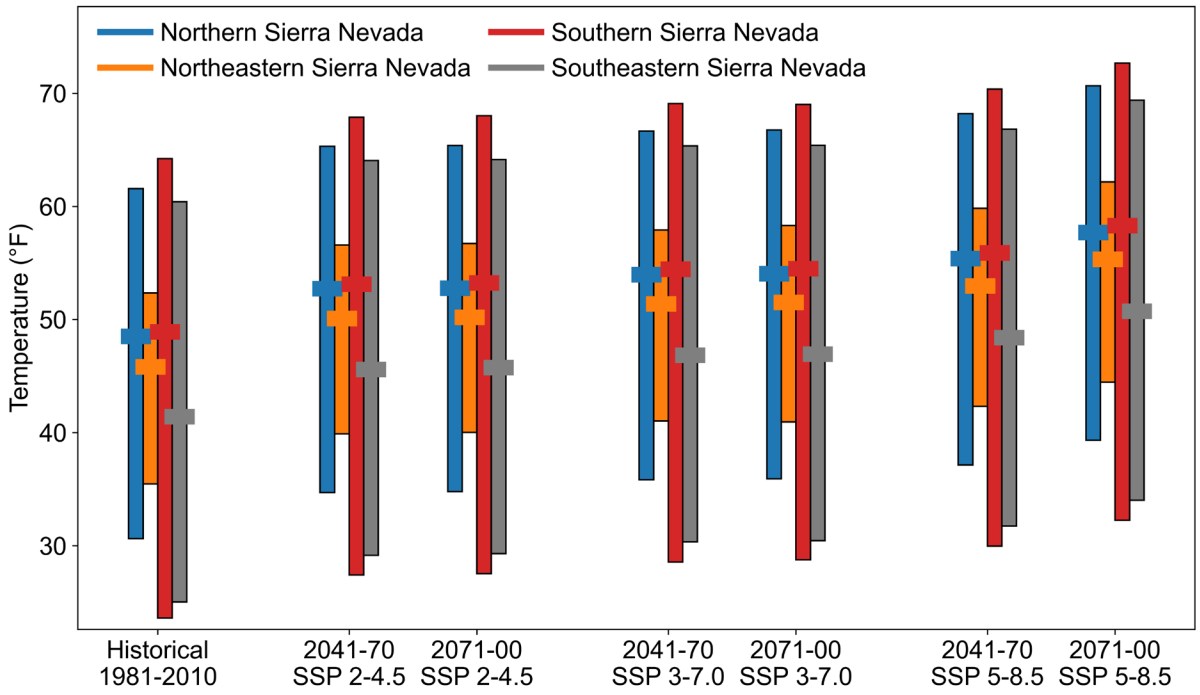


Figure 2.4: *Thirty-year average temperatures and their spatial variation (maximum, average, and minimum) in each subregion of Sierra Nevada under historical conditions (1981–2010) and future projections (mid-century: 2041–2070, end-century: 2071–2100) across three Shared Socio-economic Pathways (SSPs): SSP 2–4.5, SSP 3–7.0, and SSP 5–8.5.*

It is worth acknowledging that many available global climate models (GCMs) provide information at coarser spatial scales that do not adequately capture the steep gradients and microclimates of the Sierra Nevada (Dettinger, 2015). Although statistically downscaled climate projections from a wide range of SSPs are available at ~3 km resolution, dynamical downscaling has been limited to few pathways and variables (both datasets are available in the Cal-Adapt Analytics Engine). Dynamical downscaling is important because it better represents topography, snowpack processes, and local feedback that coarser models often miss (Rahimi, 2023). Similarly, hydrologic projections often only include a subset of GCMs that are carefully selected to capture a broad range of future climate trends and variability across warming magnitudes and precipitation responses.

Table 2.1: *Projected changes (ensemble mean ±1 standard deviation), relative to historical (1981–2010) average, in maximum temperature (T_{max}), minimum temperature (T_{min}), and precipitation (P) for the Sierra Nevada and its four subregions by the mid-century (2041–2070) and end-century (2071–2100) under three SSPs, SSP 2–4.5 (n=32), SSP 3–7.0 (n=62), and SSP 5–8.5 (n=34). A lower standard deviation relative to the mean value indicates strong inter-model agreement and higher confidence.*

SSP	Time Period	Variable	Sierra Nevada	Northeastern Sierra Nevada	Northern Sierra Nevada	Southeastern Sierra Nevada	Southern Sierra Nevada
SSP 2–4.5	mid-century	T_{max} (°C)	4.29±0.17	4.46±1.12	4.21±0.99	4.40±1.10	4.26±1.06
SSP 3–7.0	mid-century	T_{max} (°C)	4.36±0.20	4.56±1.00	4.24±0.88	4.60±1.00	4.35±0.91
SSP 5–8.5	mid-century	T_{max} (°C)	5.60±0.22	5.80±1.24	5.46±1.15	5.70±1.20	5.64±1.21
SSP 2–4.5	end-century	T_{max} (°C)	5.65±0.24	5.88±1.42	5.50±1.29	5.90±1.40	5.65±1.33
SSP 3–7.0	end-century	T_{max} (°C)	6.95±0.32	7.34±1.58	6.78±1.40	7.20±1.40	6.90±1.38
SSP 5–8.5	end-century	T_{max} (°C)	9.32±0.39	9.72±2.02	9.04±1.82	9.70±2.00	9.36±1.84
SSP 2–4.5	mid-century	T_{min} (°C)	3.97±0.22	4.08±1.06	3.93±0.94	4.00±0.80	3.95±0.81
SSP 3–7.0	mid-century	T_{min} (°C)	4.14±0.21	4.26±0.80	4.06±0.76	4.30±0.70	4.15±0.70
SSP 5–8.5	mid-century	T_{min} (°C)	5.26±0.24	5.40±1.26	5.18±1.14	5.30±0.90	5.28±0.99
SSP 2–4.5	end-century	T_{min} (°C)	5.30±0.29	5.48±1.30	5.21±1.20	5.40±1.10	5.29±1.15
SSP 3–7.0	end-century	T_{min} (°C)	6.82±0.29	7.04±1.40	6.67±1.32	7.00±1.20	6.85±1.30
SSP 5–8.5	end-century	T_{min} (°C)	9.13±0.36	9.40±2.18	8.93±2.00	9.30±1.80	9.19±1.85
SSP 2–4.5	mid-century	P (%)	2.0±7.0	4.6±7.2	1.0±6.8	6.0±9.0	0.9±8.6
SSP 3–7.0	mid-century	P (%)	2.0±7.0	4.6±7.4	-0.1±7.6	8.0±10.0	0.1±9.0
SSP 5–8.5	mid-century	P (%)	2.0±8.0	5.2±7.2	-0.3±6.6	10.0±14.0	0.5±10.5
SSP 2–4.5	end-century	P (%)	3.0±7.0	7.2±9.0	1.6±7.4	7.0±10.0	0.4±8.5
SSP 3–7.0	end-century	P (%)	5.0±8.0	8.8±9.0	1.9±8.0	12.0±10.0	1.6±9.4
SSP 5–8.5	end-century	P (%)	5.0±12.0	10.6±12.2	2.3±9.6	17.0±22.0	1.6±13.5

Also, in response to future emissions scenarios, different GCMs produce a range of outcomes. Therefore, modern climate projections are best interpreted using model ensembles, incorporating multiple emissions pathways and underlying assumptions, which help assess the level of agreement and uncertainty across multiple models. In this report, climate projections are based on all GCMs available through Cal-Adapt, downscaled using the Localized Constructed Analogs, version 2 (LOCA2) method. Historical climate projections were developed using an ensemble of 15 GCMs and their 70 ensemble members. Future projections were derived from 13–15 GCMs, with 33–62 ensemble members depending on the specific SSPs, to capture the full range and consensus of potential climate outcomes.

Box 2.1: *Cold-Air Pooling and Fine-Scale Modulation of Temperature and Snow Persistence in Complex Terrain*

Cold-air pooling (CAP) is a local atmospheric process that occurs in complex terrain during clear, calm conditions, when radiative cooling causes dense air near the surface to fall downslope and accumulate in valley bottoms and topographic depressions. Consequently, minimum temperatures (T_{min}) in these locations can be substantially lower than the surrounding landscape, even under climate change-induced warming. However, CAP is not resolved by the coarse-resolution climate models and is therefore generally not present in regional climate change assessments.

Fine-scale climate modeling studies that incorporate terrain attributes such as slope, curvature, and relative elevation demonstrate that CAP mainly affects T_{min}, with limited influence on T_{max} or precipitation. While CAP does not alter large-scale warming trends, it can delay local snowmelt and modestly increase the persistence of spring snowpack in valley bottoms and mid-elevation basins where cold air is trapped beneath surrounding topography. Incorporating CAP into downscaled climate projections can increase April 1 snowpack persistence by a small margin (~6.5%) compared to models that do not include it (Curtis et al., 2014).

Although the hydrological consequences of CAP for runoff timing and soil moisture are secondary and location-specific, its ecological relevance is more pronounced. By sustaining cooler microclimates and delaying snowmelt in certain locations, CAP can contribute to the formation of climate refugia and influence vegetation patterns and habitat suitability under future climates (Wilkin et al., 2016; Pastore et al., 2022).

Thus, CAP does not change the long-term warming, snowpack decline, and hydrologic trends summarized in this chapter; rather it should be viewed as a fine-scale modifier of climate impacts in a topographically complex landscape.

By the final 30 years of this century (2071–2100), climate models project consistent warming across the Sierra Nevada regions, and subregions, under all emission scenarios (**Table 2.1, Figure 2.2, Figure 2.3,** and **Figure 2.4**). Relative to 1981–2010, projected increases (mean ± 1 SD) in maximum temperature (T_{max}), averaged over the entire Sierra Nevada, are approximately 5.65±0.24°F under SSP 2–4.5, 6.95±0.32°F under SSP 3–7.0, and 9.32±0.39°F under SSP 5–8.5. Corresponding increases in minimum temperature (T_{min}) are 5.30±0.29°F, 6.82±0.29°F, and 9.13±0.36°F under SSP 2–4.5, SSP 3–7.0, and SSP 5–8.5, respectively. These trends are consistent across the four subregions (**Table 2.1**) and at the level of individual basins (defined using Hydrologic Unit Code 8 or HUC-8) (**Table A1**). However, we do see pockets of extreme warming zones throughout the region at scales smaller than HUC-8 (**Figure 2.2, Figure 2.3**). The level of projected warming is consistent across models, scenarios, and subregions, suggesting a very likely outcome (≥90% probability, with unanimous model agreement on the sign of change) and very high confidence. Although year-to-year variability and the magnitude of long-term trends differ among models, the direction and robustness of projected warming are consistent. Local deviations from regional minimum temperature trends may occur in complex terrain due to cold-air pooling (**Box 2.1**) (Curtis et al., 2014; Lundquist et al., 2008).

Future changes in precipitation are less certain than temperature. Across all SSPs, end-century (2071–2100) changes in regional ensemble means are generally modest, ranging between 3.0±7.0% under SSP 2–4.5, 5.0±8.0 under SSP 3–7.0, and 5.0±12.0% under SSP 5–8.5 (**Table 2.1**). Looking at the end-century changes at subregional scales under SSP 5–8.5 (*worst-case*) scenario, the Northeastern Sierra Nevada and Southeastern Sierra Nevada subregions are projected to become slightly wetter, with mean precipitation increases of 10.6±12.2% and 17.0±22.0%, respectively. Although Northern Sierra Nevada and Southern Sierra Nevada (**Figure 1.1**) are projected to experience minimal change (shown by brown color in **Figure 2.5**), a large portion of these regions show consistent drying (**Figure 2.5**), with mean end-century changes of ~2.3±9.6% and 1.6±13.5% under SSP 5–8.5, respectively. Across all regions, basins and SSPs, individual model

projections span from ~-26 to +78% in extreme cases (**Table A2**). Despite this spread, agreement among models remains relatively high, with 42–97% of models projecting changes in the same direction (**Table A2**). Overall, projected long-term changes in precipitation remain within roughly -0.3 to +17.0% for subregion-averaged ensemble means, which is small relative to California's historically high interannual precipitation variability, normally ranging from ~50–200% (Dettinger et al., 2011).

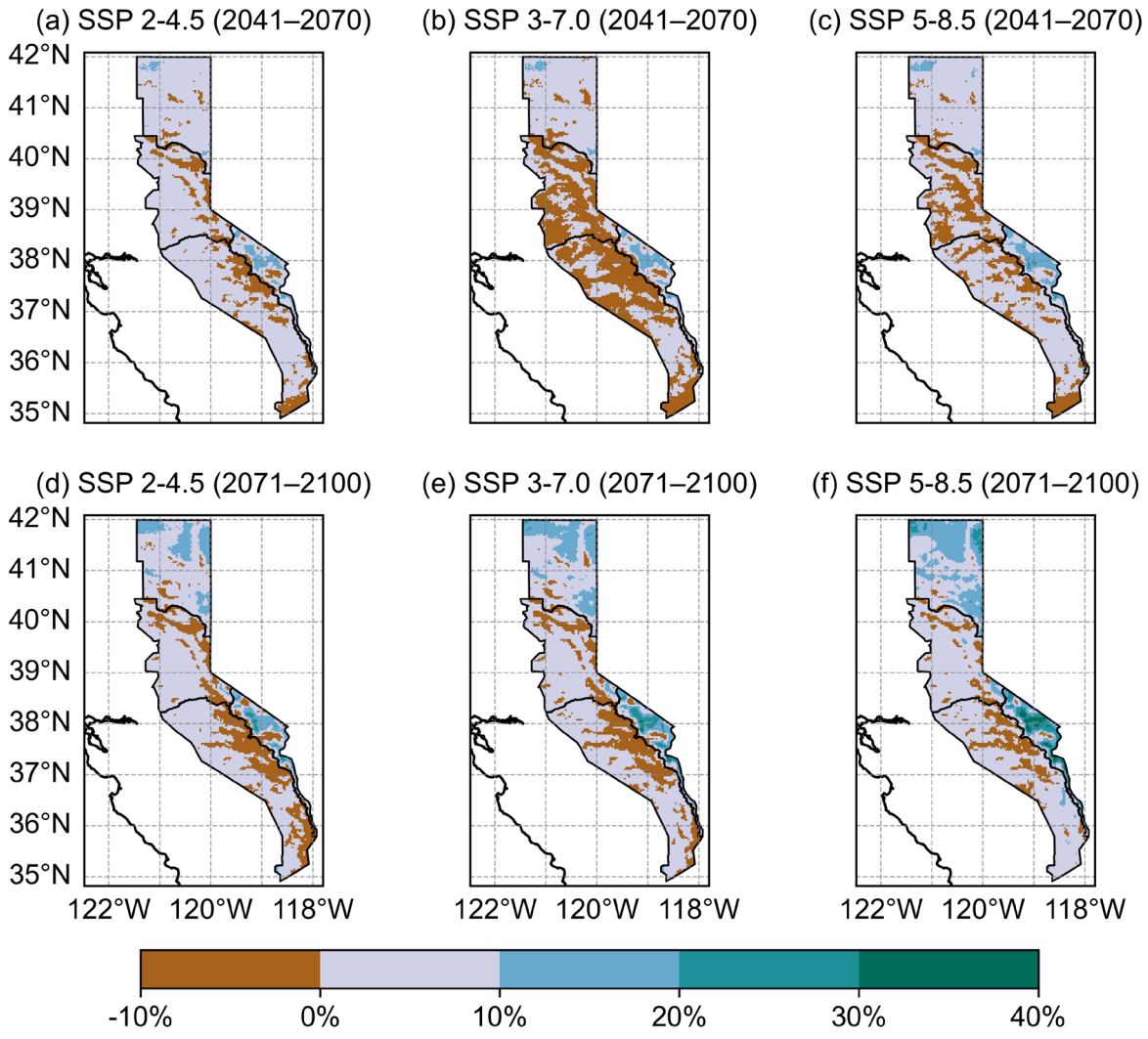


Figure 2.5: *Projected changes in precipitation for 2041–2070 (a, b, c) and 2071–2100 (d, e, f), under SSP 2–4.5 (a, d), SSP 3–7.0 (b, e) and SSP 5–8.5 (c, f).*

Although long-term average changes in precipitation may appear modest, numerous studies (Ullrich et al., 2018; Berg & Hall, 2015) suggest substantial shifts in the intensity, frequency, and sequencing of precipitation events. In almost all areas of the Sierra Nevada, the precipitation from the most extreme storm events, including maximum annual 3-day totals (CDWR, 2015) and atmospheric rivers (Espinoza et al., 2018), is projected to increase between 5–30%. Polade et al.

(2017) also found that California is likely to experience more dry days, however, these dry periods are increasingly interrupted by stronger storms in between. In other words, although the frequency of storms may decrease, the intensity of individual events is projected to rise, while the average storm size remains largely unchanged. Expanding on this, Huang et al. (2020) applied a targeted dynamically downscaling framework to extreme atmospheric river storms and found a 10–40% increase in total accumulated precipitation, especially in valleys and on the leeward sides of the Sierra Nevada mountains. Similarly, Swain et al. (2018) and Williams et al. (2022) emphasized the growing susceptibility of Mediterranean climates like California to rapid transitions between drought and flood conditions. Their findings project a 25–100% increase in extreme dry-to-wet precipitation events. These changes are expected to amplify flood, erosion, and debris-flow risks, with implications for water resources, built systems, and social systems throughout the region (see *Section 3.2 Water Resources*, Chapter 4, and Chapter 5).

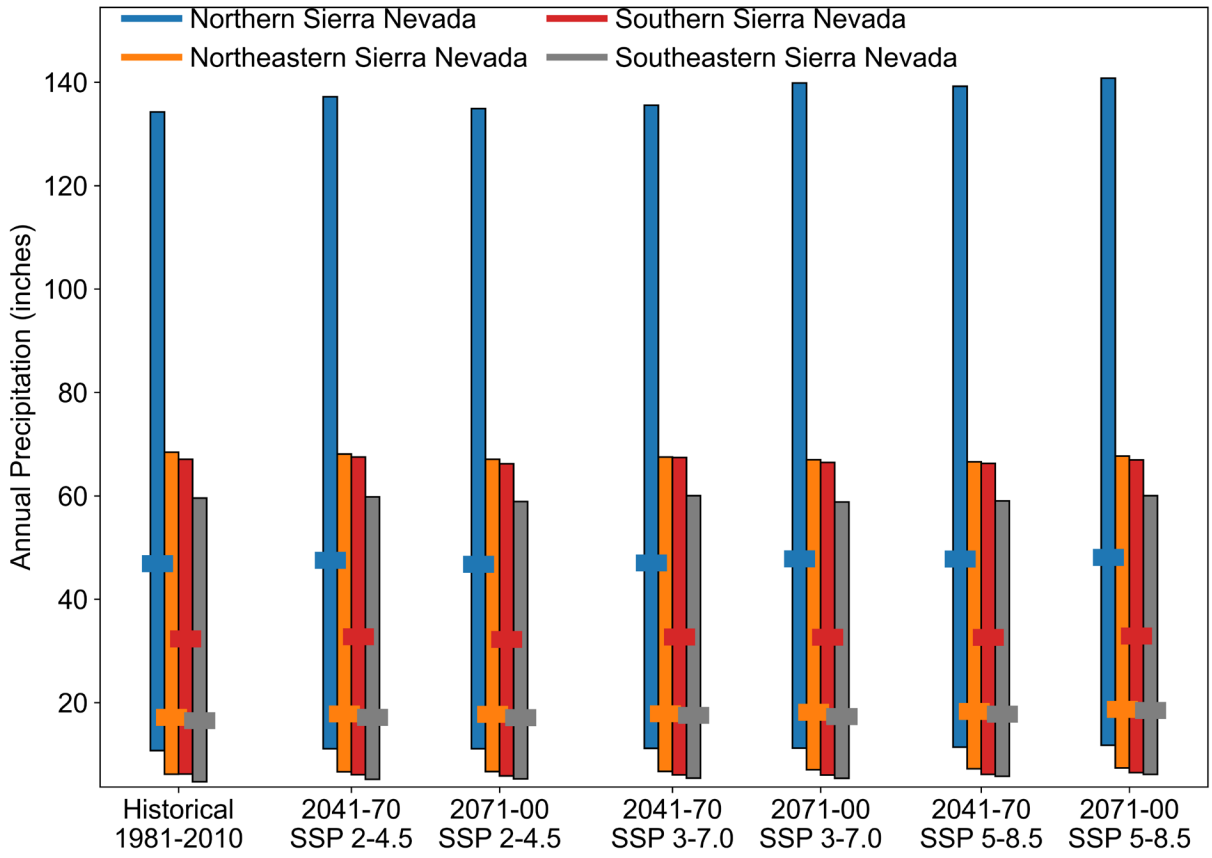


Figure 2.6: *Thirty-year average precipitation and their spatial variation (maximum, average and minimum) in each subregion of the Sierra Nevada under historical conditions and future mid-century (2041–2070) and end-century (2071–2100) projections across three Shared Socio-economic Pathways (SSPs): SSP 2–4.5, SSP 3–7.0, and SSP 5–8.5.*

These climate-driven changes exhibit pronounced elevation dependence across the Sierra Nevada region. The Fourth Assessment projected systematic elevation gradients in warming, precipitation, snowpack loss, and soil moisture, with higher elevations warming faster than lower elevations and a modest increase (~10%) in precipitation at higher elevations (>6,000 ft)

by 2070–2099 (Dettinger et al., 2018). This pattern of amplified warming at higher elevations is consistent with elevation-dependent warming observed in other regions of the world (Pepin et al., 2022). Dettinger et al. (2018) projected an increase in rain-snow transition elevation by ~1,500–3,000ft (457–914 m) under 6–10°F (3.3–5.5°C) warming. Consistent with this broad regional assessment, Cui et al. (2023) predicted an increase in rain-snow transition elevation by ~984 ft (300 m) under a 3.6°F (2°C) warming in the American River Basin.

2.3 Snowpack Trends

Snow contributes to an estimated 70% of the total runoff in mountain areas and up to two thirds of the inflow to the major reservoirs in the western United States (Li et al., 2017). In California, Sierra Nevada snowpack is a major component of the state's water storage infrastructure (CDWR, 2025). The Sierra Nevada snowpack has been largely declining, between 20–80%, reflecting on broader shrinking snowpack trends observed across the western United States (Mote et al., 2018). These reductions, along with lower snow to rain ratio, more frequent rain-on-snow events, and earlier melt, are driven by rising temperatures (Hale et al., 2023; Cho et al., 2021; Welty & Zeng, 2021; Safeeq et al., 2015; Harpold et al., 2012). However, Mote et al. (2018) also show positive trends in snowpack in few locations, especially in Northern Sierra Nevada and along the rain-snow line in Southern Sierra Nevada. These diverging trends may be driven by changes in precipitation or fine-scale temperature processes such as cold-air pooling are present (**Box 2.1**) (Curtis et al., 2014; Lundquist et al., 2008).

Table 2.2: *Projected changes (ensemble mean ±1 standard deviation in %), relative to historical (1981–2010) average, in April 1 Snow Water Equivalent (SWE) for the Sierra Nevada and its four subregions by the mid-century (2041–2070) and end-century (2071–2100) under three SSPs, SSP 2–4.5 (n=4), SSP 3–7.0 (n=4), and SSP 5–8.5 (n=4). A lower standard deviation relative to the mean value indicates strong inter-model agreement and higher confidence.*

SSP	Time Period	Sierra Nevada	Northeastern Sierra Nevada	Northern Sierra Nevada	Southeastern Sierra Nevada	Southern Sierra Nevada
SSP 2–4.5	mid-century	-47±12	-52±26	-55±17	-50±18	-35±14
SSP 3–7.0	mid-century	-58±15	-70±15	-65±9	-56±23	-42±18
SSP 5–8.5	mid-century	-60±14	-72±16	-67±15	-60±25	-46±16
SSP 2–4.5	end-century	-67±16	-71±12	-77±9	-65±5	-53±12
SSP 3–7.0	end-century	-74±14	-81±9	-84±8	-58±21	-60±15
SSP 5–8.5	end-century	-84±12	-93±4	-91±5	-74±19	-71±10

Persistent low-to-no snow conditions are projected to continue and amplify (**Figure 2.7**), despite modest changes in precipitation as the precipitation phase largely depends on temperature. These low-to-no snow conditions are expected to occur sooner across California than in other regions of the western United States (Siirila-Woodburn et al., 2021). Our analysis of simulations using the Variable Infiltration Capacity (VIC) hydrologic model (Liang et al., 1994) forced with the boundary conditions from four CMIP6 GCMs (CNRM-ESM2-1, EC-Earth3-Veg, GFDL-ESM4, MPI-ESM1-2-HR) revealed that April 1 SWE is projected to decline substantially across the Sierra Nevada and all emissions scenarios (**Table 2.2**), with strong agreement among models on the direction of change (100% of models projecting declines; **Table A3**). By mid-century (2041–2070), the average April 1 SWE across the region is expected to decline by 47±12% under SSP 2–4.5, 58±15% under SSP

3–7.0, and 60±14% under SSP 5–8.5. Corresponding declines by the end-century (2071–2100) are projected to be 67±16% under SSP 2–4.5, 74±14% under SSP 3–7.0, and 84±12% under SSP 5–8.5 (**Table 2.2**). Looking at the subregional scales, Southern Sierra Nevada appears to be slightly less sensitive (in relative terms) compared to the other three regions. Northern Sierra Nevada and Northeastern Sierra Nevada show the greatest decline in all but one HUC8 basin with over 80% reduction in April 1 SWE by the end-century under SSP 3–7.0 and by over 90% under SSP 5–8.5 (**Table A3**). In the Eastern Sierra Nevada, where snowpack is already low, it is expected to be nearly absent by the year 2100 under SSP 5–8.5 (*worst-case* scenario) (**Figures A1-A3**). While the magnitude of change varies by subregion, scenario, and model, agreement among models on widespread SWE loss is very high across all periods and scenarios, underscoring the robustness of projected snowpack reductions while also highlighting pronounced spatial and scenario-dependent uncertainty in the magnitude of change.

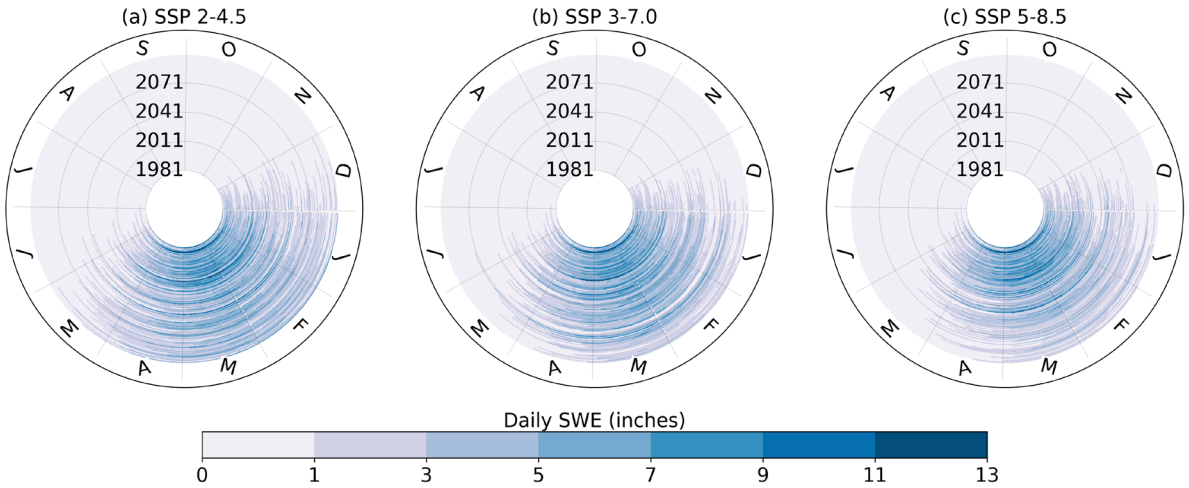


Figure 2.7: *Projected Sierra Nevada average daily snow water equivalent (SWE) under SSP 2–4.5 (a), SSP 3–7.0 (b) and SSP 5–8.5 (c). Circular lines represent daily SWE for each water year (1981–2100), radial lines mark months (Oct–Sept), and colors indicate SWE depth.*

Recent studies support these findings. Sun et al. (2019) predict, under high emission scenarios (i.e., RCP 8.5), only about 36% (±12%) of historical April 1 SWE in the Sierra Nevada by the end of the century in many lower-elevation basins. Looking at the entire western United States, Schmitt et al. (2024) estimated that the exceptionally low snowpack conditions observed between 1921–2011 could occur five (under SSP 2–4.5) to nine (under SSP 5–8.5) times more frequently by 2100. Shulgina et al. (2023) show higher climate change sensitivity of peak season atmospheric river-related snowlines, increasing by ~700 m (~2,300 feet), compared to other storms, increasing by ~600 m (~2,000 feet) under RCP 8.5.

These snowpack reductions are not expected to be uniform across seasons or geographic areas. The model results indicate that the biggest declines are projected to occur in February and April in the Northern Sierra Nevada, and in January and March in the Northeastern Sierra Nevada. By mid-summer, the Sierra Nevada snowpack is expected to be mostly melted (**Figure 2.8**), resulting in limited water availability during the dry months. As a result, the water that flowed out of the range earlier in the year will no longer contribute to summer runoff, streamflow, soil moisture, or

groundwater recharge. Warming temperatures increase the likelihood of rain rather than snow at any given location, resulting in less of the range receiving snow initially. Additionally, there will be more opportunity for early snowmelt, causing snowpacks to accumulate less and persist for shorter periods compared to historical conditions.

2.4 Trends in Regional Drying and Runoff

Reductions in snowpack, a larger part of precipitation falling as rain rather than snow, increased precipitation intensity, and more frequent rain-on-snow events are expected to alter the seasonal distribution of streamflow. These changes typically result in decreased summer streamflow and increased runoff during winter and spring. Observations already show that earlier snowmelt is altering streamflow patterns across the western United States, with peak runoff in snow-fed rivers such as the Sacramento River, occurring up to a month earlier than historical averages (Milanes et al., 2022; Fritze et al., 2011). Projections from VIC further indicate that under all SSPs, winter (January–March) runoff may likely increase (**Figure 2.9, Table 2.3**). Spring (April–June) and summer (July–September) runoffs are expected to decrease substantially (**Figure 2.9, Table 2.3**). Depending on the region and climate scenario, annual total runoff is projected to range from 88±21% to 121±12% of historical levels, suggesting relatively modest changes at the

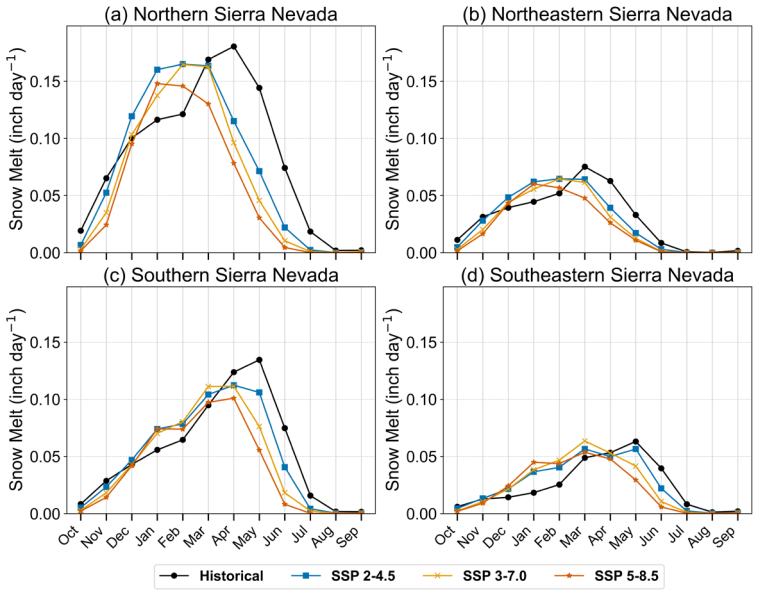


Figure 2.8: *Monthly average snowmelt (actual values) for four subregions of the Sierra Nevada—(a) Northern Sierra Nevada, (b) Northeastern Sierra Nevada, (c) Southern Sierra Nevada, and (d) Southeastern Sierra Nevada—comparing the historical period with future projections under SSP 2–4.5, SSP 3–7.0, and SSP 5–8.5 by end-century (2071–2100).*

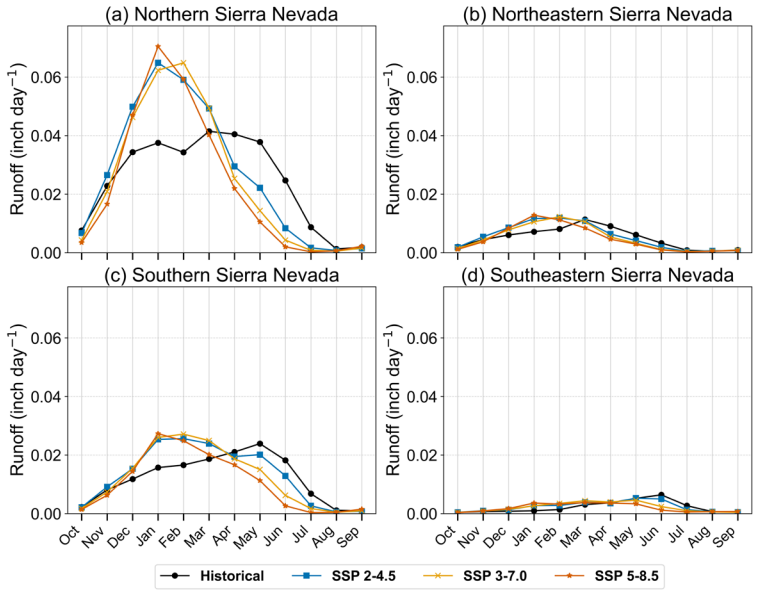


Figure 2.9: *Monthly average runoff (inch per day) for four subregions of the Sierra Nevada—(a) Northern Sierra Nevada, (b) Northeastern Sierra Nevada, (c) Southern Sierra Nevada, and (d) Southeastern Sierra Nevada—comparing the historical period with future projections for SSP 2–4.5, SSP 3–7.0 and SSP 5–8.5 by end-century (2071–2100).*

annual scale. In contrast, summer runoff is expected to decline substantially, reaching as low as 41%±10% of historical averages under SSP 3–7.0 and 32%±7% under SSP 5–8.5 in the Northern Sierra Nevada. Data specific to individual HUC-8 basins are presented in **Table A4**.

These findings are consistent with previous studies. For example, snowmelt-driven runoff is expected to shift as much as 80 days earlier by 2100, under RCP 8.5 (Schwartz et al., 2017), and snowmelt-derived runoff is projected to decline by one-third across the western United States under the same scenario (Li et al., 2017). Some Northern Sierra Nevada watersheds exhibit substantial groundwater connectivity and baseflow contributions to total runoff. These watersheds may show a greater runoff sensitivity, especially at longer time scales, to climate warming relative to watersheds in the Southern Sierra Nevada with very little to no summer baseflow (Safeeq et al., 2014). Climate sensitivity to runoff timing shows an opposite pattern with Southern Sierra Nevada watersheds showing greater impact (Null et al., 2010), mainly due to their higher reliance on snowmelt runoff.

Table 2.3: *Average (ensemble mean ±1 ensemble standard deviation) projected change (calculated as a ratio of future runoff divided by historical (1981–2010) and then multiplied by 100) in water-year and seasonal runoff for the Sierra Nevada and its four subregions by the mid-century (2041–2070) and end-century (2071–2100) under three SSPs, SSP 2–4.5 (n=4), SSP 3–7.0 (n=4), and SSP 5–8.5 (n=4). A lower standard deviation relative to the mean value indicates strong inter-model agreement and higher confidence.*

SSP	Time Period	Timescale	Sierra Nevada	Northeastern Sierra Nevada	Northern Sierra Nevada	Southeastern Sierra Nevada	Southern Sierra Nevada
SSP 2–4.5	mid-century	water-year	106±11	106±7	102±8	114±15	108±15
SSP 3–7.0	mid-century	water-year	102±17	104±12	99±16	108±28	101±21
SSP 5–8.5	mid-century	water-year	99±3	101±3	97±2	107±12	96±7
SSP 2–4.5	end-century	water-year	111±13	111±10	107±12	121±12	112±16
SSP 3–7.0	end-century	water-year	103±13	101±11	98±9	118±17	104±19
SSP 5–8.5	end-century	water-year	93±18	96±11	91±16	110±33	88±21
SSP 2–4.5	mid-century	January-March	109±9	111±8	107±6	125±24	108±16
SSP 3–7.0	mid-century	January-March	99±10	101±16	99±14	112±23	96±18
SSP 5–8.5	mid-century	January-March	101±18	99±23	102±19	115±33	100±23
SSP 2–4.5	end-century	January-March	119±10	124±5	123±12	130±34	111±10
SSP 3–7.0	end-century	January-March	108±18	107±20	106±11	137±55	106±29
SSP 5–8.5	end-century	January-March	99±18	103±9	98±18	135±58	92±24
SSP 2–4.5	mid-century	July-September	82±4	86±5	67±6	84±9	89±5
SSP 3–7.0	mid-century	July-September	75±14	74±10	62±14	76±19	84±19
SSP 5–8.5	mid-century	July-September	68±5	74±6	56±7	71±5	73±5
SSP 2–4.5	end-century	July-September	76±9	74±8	55±12	84±18	87±15
SSP 3–7.0	end-century	July-September	58±12	59±7	41±10	65±18	65±18
SSP 5–8.5	end-century	July-September	45±13	55±6	32±7	47±22	48±19

While most modeling studies agree on reduction in streamflow during summer, the exact amount of reduction in streamflow depends on climate and hydrological models used and remain uncertain (Miller et al., 2021). These reductions in streamflow are accompanied by declining summer soil moisture across the Sierra Nevada, with 50–100% model agreement indicating decreases of up to 33.5±5% relative to historical conditions (**Figure 2.10; Table A5**). Under the *intermediate* scenario, December–February and March–May soil moisture show an increase, which reduces to high elevations only under *high* and *worst-case* scenarios. June–August and September–November soil moisture shows drying patterns across the region, except for some modest wetting in the Southeastern Sierra Nevada (**Figure 2.10**).

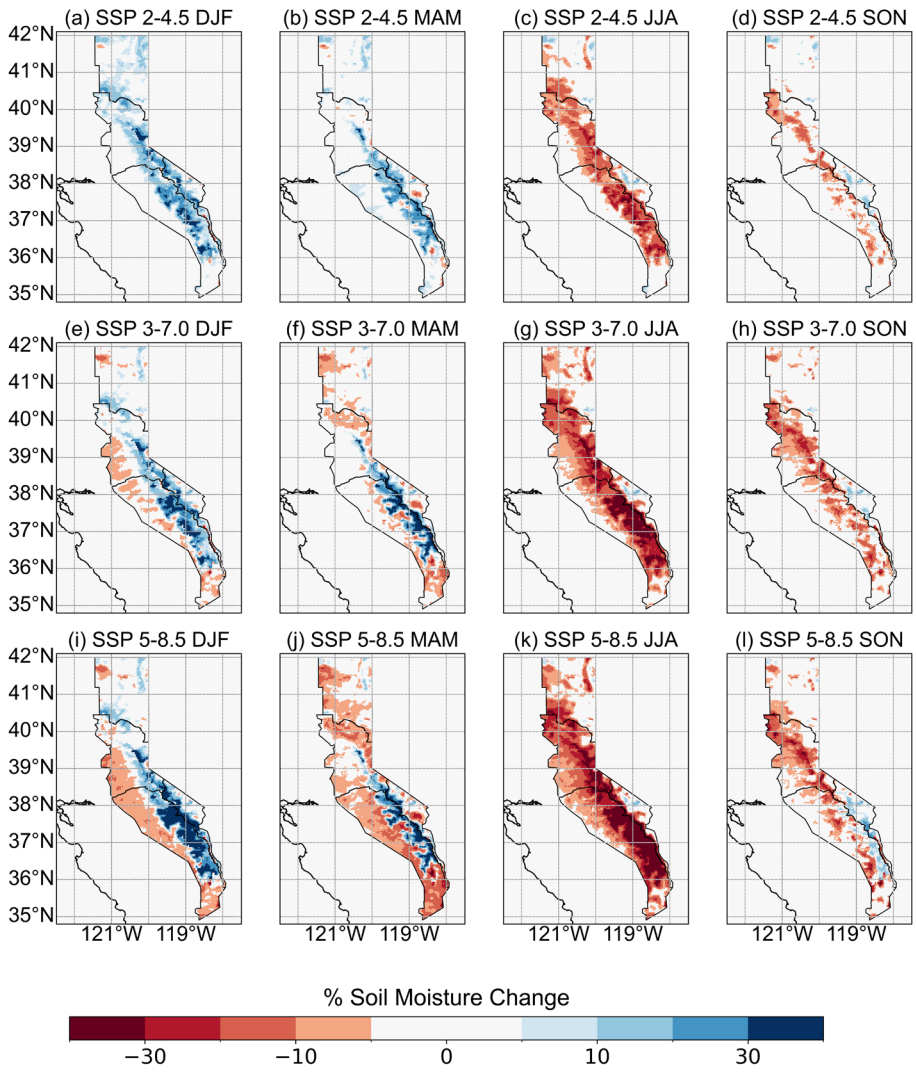


Figure 2.10: *Percent changes in soil moisture (multi-model average) by 2071–2100 compared to 1981–2010 in (a) DJF: December-January-February, (b) MAM: March-April-May, (c) JJA: June-July-August, and (d) SON: September-October-November for SSP 2–4.5 (top row), SSP 3–7.0 (middle row), and SSP 5–8.5 (bottom row).*

To synthesize the magnitude, direction, and confidence of observed and projected hydroclimatic changes across the Sierra Nevada, we summarize key climate and hydrological variables in **Table**

2.4, with explicit comparison to findings from California's Fourth Climate Change Assessment.

Table 2.4: *Summary of observed and projected changes in key climate and hydrological variables across the Sierra Nevada region based on California's Fifth Climate Change Assessment (CCCA5), with comparisons to California's Fourth Climate Change Assessment (CCCA4). The table highlights relative magnitudes, direction of changes, and seasonal shifts, and summarizes confidence in future change.*

Climate impacts	Historical trends (CCCA5, relative to CCCA4)	Future direction of change (CCCA5)	Confidence for future change
Maximum temperature (T_{max})	Historical warming across Sierra Nevada consistent with CCCA4. CCCA4 documented late-century warming of ~9–10°F under high emissions. This shows an amplified rate of warming compared to observed trends, 4.9°F/century since 1981.	CCCA5 projects continued warming with an increase of 5.65±0.24°F (SSP 2–4.5) to 9.32±0.39°F (SSP 5–8.5), by the end-century, broadly consistent with CCCA4 magnitudes under comparable forcing, with clearer subregional and basin-scale detail.	Very High
Minimum temperature (T_{min})	Historical nighttime warming is consistent with CCCA4's overall temperature increases, though T_{min} was not reported separately in CCCA4. Historical trends show a warming of T_{min} at a rate of 8.9°F/century since 1981.	CCCA5 shows T_{min} warming (5.30±0.29°F under SSP 2–4.5 to 9.13±0.36°F under SSP 5–8.5) comparable to T_{max}, while highlighting potential for stronger T_{min} increases in individual basins.	Very High
Annual precipitation	Historically high interannual variability dominates long-term trends, consistent with CCCA4. CCCA4 reported small and uncertain long-term changes (about -10% to +15%), with variability far exceeding mean trends. Trends in observational records are inconclusive.	CCCA5 confirms modest subregional mean changes by mid-to late-century (roughly 3.0±7.0% to 5.0±12.0%) and between -0.3±6.6% and 17.0±22.0 at subregional scales, broadly consistent with CCCA4. CCCA5 adds clearer spatial differentiation (e.g., wetter Northeastern and Southeastern Sierra Nevada, minimal change or slightly drying elsewhere). Despite modest mean changes, both assessments show robust increases in extreme precipitation (5–30%) and more dry days punctuated by stronger storms.	Medium (means); High (extremes)
Snowpack (SWE)	Declining snowpack across the Sierra Nevada, consistent with CCCA4's documentation of widespread losses (eradicated below 6000 feet and by as much as 60% at higher elevations) driven by warming, rising snowlines, and earlier melt. Observed April 1 SWE has declined substantially, between 20–80% reductions, in most regions, with only limited increases.	CCCA5 confirms CCCA4 projections of widespread snowpack loss, with regional ensemble-mean April 1 SWE reductions of 47±12 to 60±14% by mid-century and 67±16 to 84±12% by end-century under moderate and worst-case emission scenarios. Snowpack is effectively eliminated at low elevations, with April 1 SWE approaching near zero in most years. These estimates fall within the range projected by CCCA4 while providing clearer spatial detail, timing, and uncertainty.	Very High
Runoff	Earlier peak runoff timing and seasonal redistribution already evident, consistent with CCCA4 projections linking warming, reduced snowpack, and earlier snowmelt to increased winter flows and reduced summer flows.	CCCA5 confirms CCCA4 findings of modest changes in annual total runoff but pronounced seasonal shifts. Annual runoff remains near historical levels (about 88–121% of baseline, depending on region and scenario), while winter and spring runoff increase and summer runoff sharply declines. Under high and worst-case emissions, Sierra Nevada average summer runoff decreases to 58% and 45%, respectively. Northern Sierra Nevada may experience up to 59% and 68% reduction in summer runoff, under high and worst-case scenarios, respectively. CCCA5 provides clear subregional and basin-scale quantification of timing of shifts and low-flow severity.	High (seasonal changes in magnitudeand timing); Medium (annual totals)

Climate impacts	Historical trends (CCCA5, relative to CCCA4)	Future direction of change (CCCA5)	Confidence for future change
Soil moisture	Long-term drying trends consistent with CCCA4, driven by warming, reduced snowpack, and increased evaporative demand. Observed and modeled declines are highest during the warm season.	CCCA5 confirms widespread declines in summer soil moisture across the Sierra Nevada, with ensemble-mean reductions of up to ~33% compared to historical conditions and 50–100% model agreement on the direction of change. Seasonal and spatial variability persists, with modest increases in some basins, but net warm-season drying intensified relative to CCCA4.	High

2.5 Trends in Wildfires

Wildfire activity in the Sierra Nevada region has intensified dramatically over the past two decades, driven by a convergence of anthropogenic climate change, historical land management practices, and increasing forest stress (Madakumbura et al., 2025; Chen et al., 2021). Rising temperatures and changing precipitation patterns are projected to increase fire activity across many regions of California by altering fuel availability and drying conditions conducive to wildfires (Krawchuk & Moritz, 2012). In the last two decades, California has experienced sixteen of the largest twenty wildfires in its recorded history (CalFire, 2025), several of which, such as the Dixie Fire (July 2021) and Caldor Fire (September 2021), originated or spread through the Sierra Nevada region, burning over 963,000 and 221,000 acres respectively. These fires exemplify the growing prevalence of high-severity, fast-moving fire events that overwhelm suppression efforts (Miller et al., 2020). The share of high-severity fires has risen sharply compared to pre-Euro American settlements (Fass, 2025). Long-term fire suppression policies, combined with reduced Indigenous cultural burning, could have contributed to unnaturally dense forests with accumulated fuels. Simultaneously, extended droughts and rising temperatures have triggered widespread tree mortality, particularly during the 2012–2016 drought when over 129 million trees died in the Southern Sierra Nevada alone (Fettig et al., 2019). Wildfires in Sierra Nevada have resulted in substantial surface fuel carbon consumption resulting in impeding productivity post-wildfire (Hemes et al., 2023). The frequency of extreme fire weather, including low humidity, and heat waves, has increased in recent years, leading to more days each year with elevated fire danger ratings (Madakumbura et al., 2025; Hino and Field, 2023). Smoke from these fires now contributes substantially to air quality degradation, which could erode more than 50% of previous multi-decadal progress in reducing fine particulate matter (PM2.5) concentrations (Burke et al., 2023). The respiratory health impacts and reduced visibility from the wildfires have been felt across the Sierra foothill communities as well as distant urban localities (Cisneros et al., 2021; Schweizer & Cisneros, 2014).

Looking ahead, the Sierra Nevada region is projected to experience more than 50% increase in annual burned areas and number of fires by 2040, depending on GHGs emissions scenarios (Gutierrez et al., 2021). Rising temperatures, earlier snowmelt, and longer dry seasons are expected to result in an earlier onset in the fire season and shift its peak into traditionally wetter months. Fuel aridity could intensify, particularly mid elevation ranges of the Sierras, where snowpack loss will expose mid-elevation forests to hotter and drier spring and summer conditions. This transition could lead to more frequent high-severity fires in previously fire-resistant zones, jeopardizing the structural integrity of coniferous forests and facilitating post-fire vegetation shifts toward shrublands and grasslands with reduced carbon sequestration potential

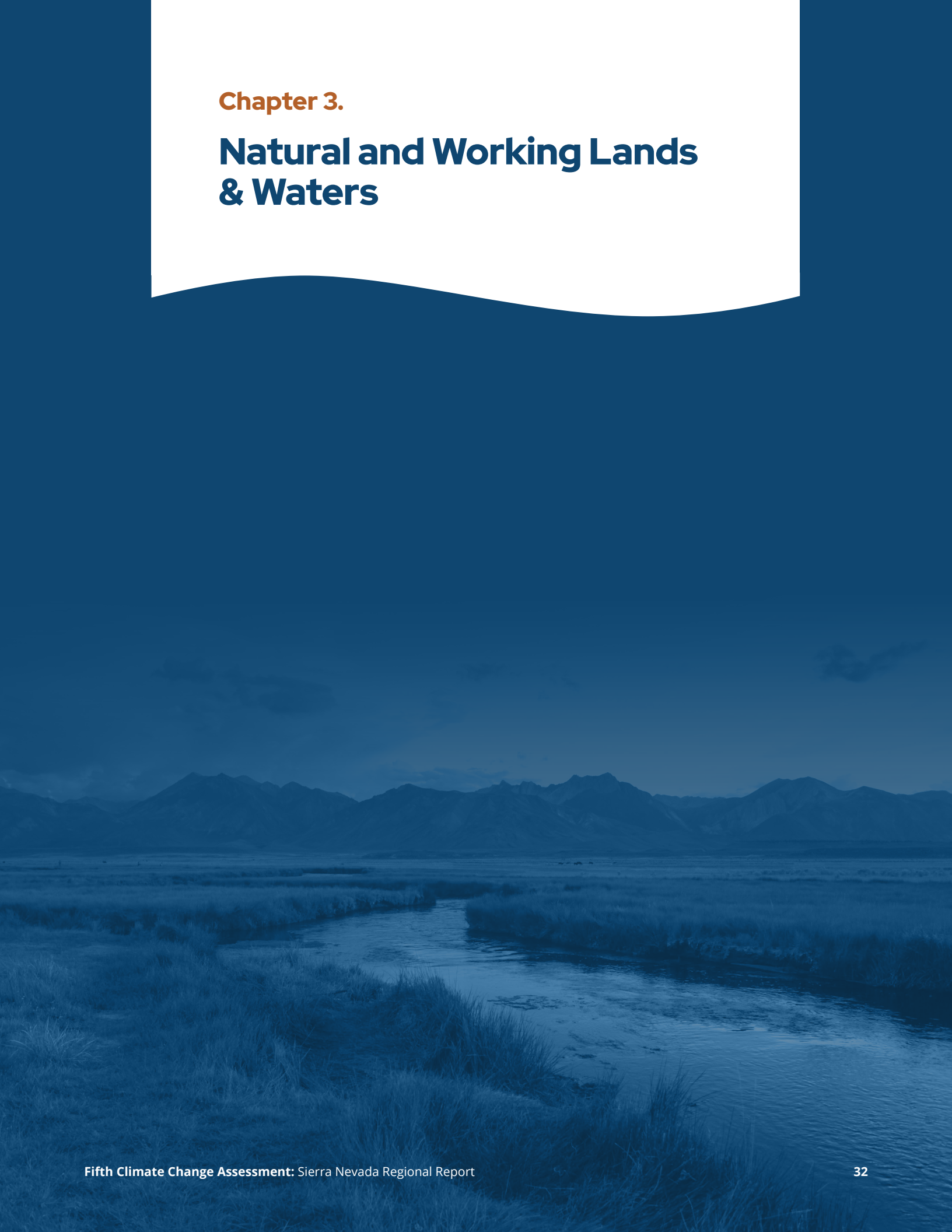
(Steel et al., 2021; Liang et al., 2017). Such ecological transitions also threaten regional hydrology, as burn scars increase erosion and sediment loads, impairing downstream reservoirs and water quality (Olsen et al., 2021). Wildfire-related emissions will further reinforce climate feedback loops (Stavros et al., 2014); already, wildfire carbon emissions in California exceed those from the state's industry or power sector in extreme fire years (Jerrett et al., 2022). To reduce risk, large-scale adaptation strategies will be essential, including expanded prescribed burns, mechanical thinning, and revitalization of Indigenous fire stewardship. However, despite growing state-level investments, only a fraction of California's high-risk forests receive treatment each year due to permitting challenges, air quality regulations, and limited operational capacity. Building future wildfire resilience in the Sierra Nevada will therefore require a coordinated, multi-jurisdictional strategy that aligns fuel management with community preparedness, post-fire recovery planning, and equitable resource distribution, especially for Tribal and underserved populations at the wildland urban interface. **Box 2.2** provides a few examples of ongoing efforts on building watershed resilience through Tribal partnership and regional collaboration.

Box 2.2: *Strengthening Forest Stewardship through Tribal Partnerships and Regional Collaboration*

Tribal partnerships have been central to these efforts. Cultural burning, practiced for centuries by Indigenous communities, is increasingly part of workforce training and forest stewardship (CNRA, 2025; CNAHC, n.d.). The Sierra-Sequoia Burn Cooperative, including the Dunlap Band of Mono Indians and the Big Sandy Rancheria Band of Western Mono Indians of California, employed cultural burning in treatments in the upper Kings River watershed in eastern Fresno County (SNC, 2021). The High Road to Tribal Forest Restoration and Stewardship, a 20-Tribe collaborative with the Sierra Institute, offered forest management training rooted in Traditional Knowledges (Sierra Institute, 2020). The Maidu Summit Consortium and the Feather River Land Trust incorporated cultural burning practices into land stewardship in an area around Plumas and Sierra counties after the Mountain Maidu reclaimed land from PG&E (Sierra Institute, 2020). The Calaveras Healthy Impact Product Solutions (CHIPS) in Calaveras county operates a millsite for bioenergy and workforce training for Tribal and other participants working on fuels reduction and forest restoration across public and private lands (CHIPS Forestry, n.d.). Regional forest management collaborative organizations such as the Eastern Sierra Wildfire Alliance, some emerging from the Regional Forest and Fire Capacity Program (RFFCP), support small businesses, workforce efforts, and volunteer action organizations (such as FireWise communities). These efforts underscore the importance of regional collaboratives to connect Tribal partners, employers, agencies, non-governmental organizations (NGOs), and community members. While these initiatives demonstrate effective partnership and stewardship models, achieving region-wide ecological and risk-reduction outcomes will require their expansion to much larger spatial and institutional scales.

Chapter 3.

Natural and Working Lands & Waters



Key Message

The Sierra Nevada faces an existential threat from climate change, which is fundamentally altering the region's ecosystems through escalating wildfire, severe drought, the stress of warming temperature and reduced snowpack, and insect outbreaks. These interconnected stressors are causing widespread forest mortality and driving a concerning conversion of forests to shrublands and grasslands, which in turn degrades critical habitat, diminishes biodiversity, and disrupts essential ecosystem functions like water regulation and carbon storage. The unique species richness and endemism, born from the area's dramatic elevational gradients, are at risk as climate shifts force wildlife to move upslope or face local extinctions, particularly for species dependent on snowpack, mature forests, or cold-water aquatic habitats. To safeguard the ecological integrity of the Sierra Nevada, proactive adaptation strategies are urgently needed, focusing on enhancing ecosystem resilience through practices such as strategic forest thinning, cultural burning, prescribed fire, restoration of degraded wet meadows and riparian areas, improving landscape connectivity to facilitate species movement in response to a rapidly changing climate, and continued experimentation with assisted migration of imperiled populations and species of plants and animals.

3.1 Terrestrial Ecosystems and Biodiversity

The California Floristic Province, which encompasses the Sierra Nevada, is recognized as a global biodiversity hotspot. The terrestrial ecosystems of the Sierra Nevada, in addition to providing critical natural resources and recreation for human populations, have a high level of species richness and endemism resulting from the large elevational gradients and mountain rain shadow effect which collectively generate a wide range of habitat conditions (Harrison et al., 2024; Baldwin et al., 2017). Key ecotones include oak woodlands in the lower elevations of the western foothills, a variety of mixed conifer forests in mid elevation to alpine environments, mountain meadows, and mixed shrubland in the eastern Sierras in the mountain rain shadow (**Figure 3.1**). In this section, we highlight key ecosystems in the Sierra Nevada, their underlying climate and disturbance sensitivities, trends in vulnerability of ecotone types, potential adaptation actions, and key underlying uncertainties in our understanding of these systems that influence recommendations for climate action.

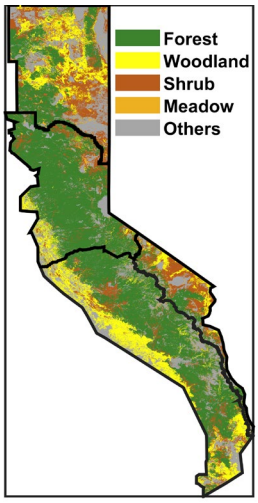


Figure 3.1: *Ecotones of the Sierra Nevada. The majority of Sierra Nevada ecosystems are dominated by closed canopy forests, more open woodlands containing a combination of trees and lower stature vegetation, or woody shrubs. Meadows dominated by annual or perennial grasses and forbs are smaller in extent but hydrologically and ecologically important components of the landscape.*

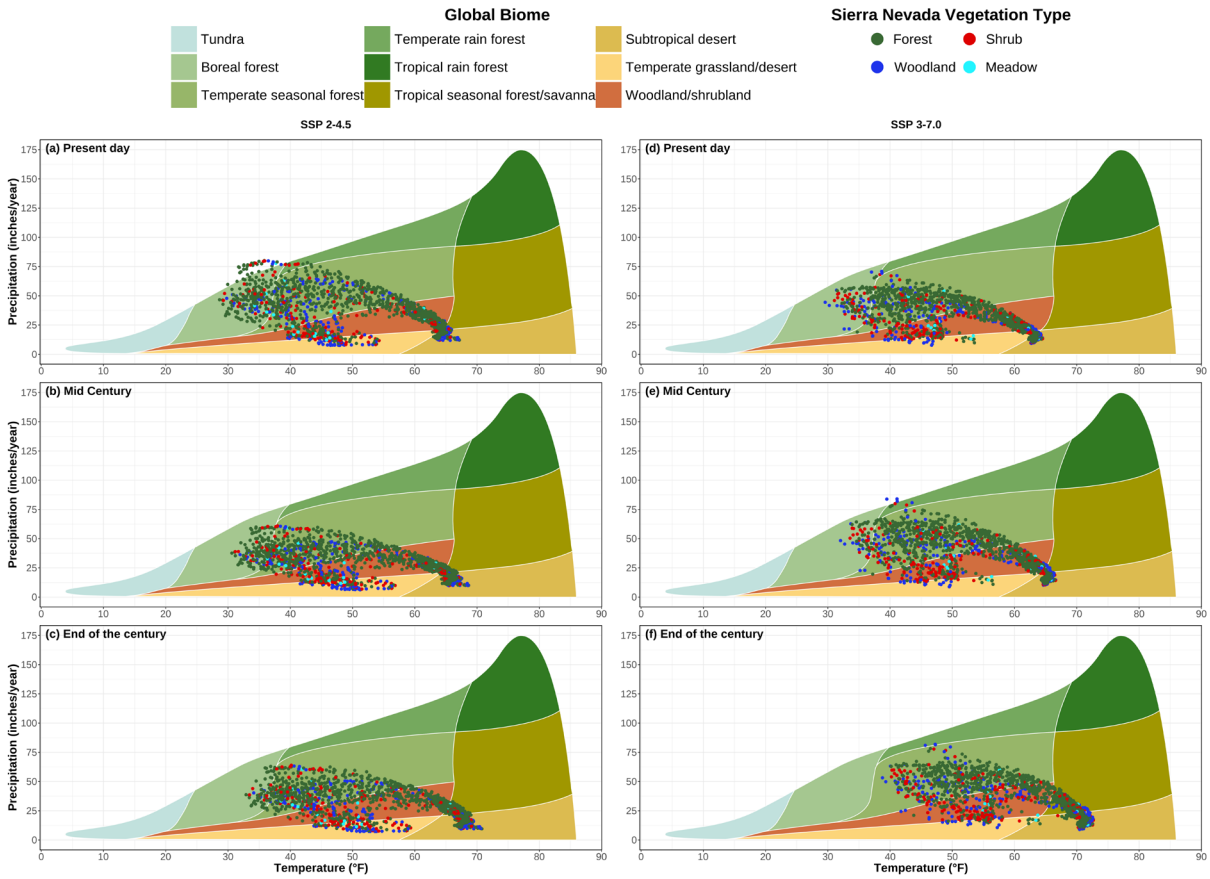


Figure 3.2: *The distribution of Sierra Nevada ecosystem types across temperature and precipitation (plotted over Whittaker life zones for reference, Whittaker, 1975) for (a) present day, (b) mid-century, and (c) end-of-century under SSP 2–4.5. Plots (d), (e), and (f) show similar plots for SSP 3–7.0. Precipitation and temperature values are derived from the ensemble mean of climate models used in this report (see Chapter 2 for climate products) under the SSP 2–4.5 and SSP 3–7.0 scenarios.*

3.1.1 Climate Effects, Trends, and Projections in Ecosystems

FOCAL ECOSYSTEMS REPRESENTING MAJOR COVER TYPES IN THE SIERRA NEVADA (FORESTS, SHRUBLANDS, RIPARIAN AND AQUATIC ECOSYSTEMS, AND OAK WOODLANDS)

The Mediterranean climate of California plays a foundational role in shaping Sierra Nevada ecosystem, phenological cycles, and ecosystem functions. Specifically, the wet winters and dry summers result in ecosystems that are strongly dependent on winter snowpack and/or winter recharge of soil moisture across a broad gradient of mean annual temperatures ranging from 30–68°F (-1–20°C). Mixed conifer forests dominate the Sierra Nevada region in terms of total spatial extent (**Figure 3.1**), breadth of climate space (**Figure 3.2**), and aboveground productivity (Bernal et al., 2022). Both climate sensitive disturbances such as drought, wildfire, insect and pathogen disturbances (Steel et al., 2023; Bernal et al., 2022; Robbins et al., 2021; Fettig et al., 2019; Stephens et al., 2018), and human disturbance and fire suppression (Stephens et al., 2018;

Stephens et al., 2015; Dolanc et al., 2014; Stephens et al., 2009) influence forest composition and structure.

Interspersed among the mixed conifer ecosystems are wet meadows, fens (i.e., peat-accumulating wetlands), streams, lakes, and other aquatic and riparian ecosystems. Although these ecosystems cover a small fraction of the landscape, they are key to sustaining biodiversity in the region, providing critical climate change refugia, contributing disproportionately to biogeochemical cycling, and are cultural keystone areas for many Indigenous groups. Riparian areas are water-dependent ecosystems that occur at the interface between terrestrial and aquatic ecosystems. In the Sierra Nevada, riparian and aquatic corridors connect high altitude lakes and streams to the valley, facilitating the transfer of water, energy, and nutrients while also providing critical habitat for amphibians, fish, aquatic invertebrates, birds, and mammals (Siegel & DeSante, 1999; Erman, 1996; Graber, 1996; Gregory et al., 1991).

Lower in elevation, the western foothills of the Sierra Nevada are occupied by California oak woodland. Though less carbon dense than their mixed conifer counterparts, the oak woodlands foster a highly diverse herbaceous understory that provides habitat for numerous vertebrate and invertebrate species. Finally, hotter and more arid locations of the Sierra Nevada are occupied by mixed shrubland. Interior chaparral characterized by evergreen shrub species are common at low elevations on the west side of the Sierras, as well as on steep, southern facing slopes at higher elevations. The chaparral ecosystems of California are a biodiversity hotspot, filled with numerous endemic plants and serve as habitat for diverse wildlife. Meanwhile, in the eastern Sierras, pinyon-juniper woodlands support species such as mule deer, bobcats, raptors, and pinyon jays. These juniper woodlands are also ecosystems of Tribal significance, providing sustenance from pinyon nuts, wood resources, and hosting sites of cultural significance. Lower in elevation, various scrub ecotypes, particularly sagebrush steppe, dominate at mid elevations where the climate is too arid for trees (Storer et al., 2004).

Fire is, and has long been, a central player in Sierra Nevada ecosystems (**Box 3.1**). Natural fire regimes range in frequency and severity across vegetation types; with frequent, low-severity fires in oak woodlands; moderately frequent and mostly low- to moderate-severity fire in mixed conifer forests; and moderately frequent moderate- to high-severity fire in shrublands (Safford et al., 2021). Meadows and riparian areas can act as fuel breaks or corridors for fire spread, depending on moisture levels and condition (Kobziar & McBride, 2006; DeBenedetti & Parsons, 1979). High densities of rhizomatous species in hydrologically connected meadows and riparian areas allow for rapid recovery and increased resilience to fire (Boisarmé et al., 2017; Willard et al., 1995; DeBenedetti & Parsons, 1979). Natural vegetation mortality drivers in mature forests outside of fire disturbance, most easily documented in forest systems at the tree level, include biotic agents (insects and pathogens), followed by competition, and then mechanical damage (Das et al., 2016). However, basic knowledge gaps remain in understanding mortality mechanisms and the interaction between abiotic and biotic stressors that ultimately result in tree mortality (Trugman et al., 2021). These uncertainties propagate through our ability to predict the vulnerability of different ecosystems to climate change and develop adaptation actions to mitigate climate change impacts.

Box 3.1: *Fire and the Sierra Nevada Ecosystem*

Fire is a central feature of the ecology of the Sierra Nevada, which has shaped the structure, distribution, and function of ecosystems for millennia (Keeley & Safford, 2016), including thousands of years of Indigenous cultural burning practices (Taylor et al., 2016). However, fire's impact varies enormously depending on the species, vegetation type, environmental setting and time of burning, all of which can be affected—directly and indirectly—by humans (Steel et al., 2015; Mallek et al., 2013). California's Indigenous Peoples 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 (Anderson, 1999). Collecting pine nuts remains an important social and cultural tradition for many Tribal communities such as Washoe, Paiute, and Shoshone. Similarly, piagi (larvae of pandora moths that feed primarily on the needles of Jeffery, lodgepole, and ponderosa pines) was a significant food source for Paiute peoples. 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 Peoples on the California coast was sharply curtailed (Kilgore, 1973) as Tribal peoples were extirpated and their land taken by Euro-American emigrants (Lindsay, 2012), though clear patterns of this in the Sierra Nevada are more uncertain. Euro-American settlement of the Sierra Nevada in the mid-19th century promoted an abrupt shift in fire regimes from frequent, low-severity burning to aggressive fire suppression. 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, subsequently altering the livelihood of Tribal peoples and their relationship to forests. Forests were particularly affected in low- to mid-elevation zones where the lack of recurring low- and moderate-intensity fires led to a buildup and increase of continuity of forest fuels (Collins et al., 2011; Anderson, 2006) and long-term shift in stand structure from few, large trees to smaller, denser trees (McIntyre et al., 2015). 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), while extreme fire weather that exacerbates wildfire severity is on the rise (Prein et al., 2022, Rother et al., 2022). The massive 2020 fire year typifies this trend, where the total burned area did not necessarily exceed a pre-colonial annual average in fire-prone ecosystems, but the high-severity burned area set new records thanks to extreme atmospheric dryness and extensive fuels in ecosystems with no recent history of fire (Safford et al., 2021). Today, yellow pine and mixed conifer forests are at high-risk of large, uncharacteristically severe wildfires that can impose long-term ecosystem damage (Safford & Stevens, 2017; Miller et al., 2009). In yellow pine and mixed conifer forests, plant species evolved with relatively frequent fires—their life histories, reproduction, and growth are intricately tied to the fire regime. Thus, changed fire regimes may have consequences for species persistence (Keeley, 2010; Webster & Halpern, 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, but also shifts in composition toward more fire- and drought-intolerant species (Dolanc et al., 2014; Collins et al., 2011; Scholl & 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). At the same time, wildfire is increasingly occurring at higher elevations, in mixed conifer and subalpine forests that historically saw very little fire and are thus not fire adapted (Xu et al., 2022). The spread of invasive species can also be facilitated by severe wildfires, and increase subsequent fire risk (Lambert et al., 2010). Ultimately, wildlife, water quality, and air resources are all tied to the spatial and temporal patterns of fires. Due to its pervasive and recurring nature across the region, fire is a central theme in this report.

TRENDS AND PROJECTIONS

Even the most optimistic climate trends and projections with the lowest level of climate change, described in Chapter 2, have substantial implications for the ecosystems of the Sierra Nevada. Most key impacts have already been observed in the past two decades. In particular, we have high confidence in trends of decreasing winter snowpack, increasing mean temperature, and increasing atmospheric dryness that are fundamentally altering the ecohydrology, biodiversity and potential carbon storage of Sierra Nevada ecosystems. Long-term warming and drying trends are shifting much of the Sierra's forested areas toward an ecosystem typically associated with shrublands, grasslands, or deserts (**Figure 3.2**). Super-imposed on these long-term trends, extreme events (e.g., droughts) are increasing in frequency and severity, causing abrupt changes

in ecosystem structure and ecosystem services. Moreover, there is a strong link between climate and fire (He et al., 2025; Moritz et al., 2012), leading to strong interactive effects between climate shifts, increasing climate extremes, and fire-related disturbance. The net result is a high likelihood of substantial vegetation type conversion (for example, from forest to shrubland) in much of the Sierra Nevada, which alters biodiversity, habitat structure, water resources, and carbon storage (Guiterman et al., 2022). During the 2011–2020 period alone, an estimated 30% of conifer forest areas in the Southern Sierra Nevada transitioned to non-forested vegetation (<25% tree canopy cover) due to massive and interrelated drought, beetle, and fire disturbance (Steel et al., 2023).

Wildfire

Projected changes in climate are associated with large increases in wildfire burned areas, including the number of wildfires and the frequency of large fires (>24,700 acres). Since the Fourth Assessment, trends in burned areas in the Sierra Nevada have continued to hit or exceed projections. This is due to increasing fire weather (defined as a set of meteorological conditions that make wildfire more likely, intense, and difficult to control), changes in forest structure, and accumulation of fuel from decades of fire suppression (Stephens et al., 2018). Climate risks include increased daily temperature extremes that explain the 30% increase in Sierra burned areas since the 1980s (Gutierrez et al., 2021). Based purely on daily maximum temperature trends, the number of fires is projected to increase by 51±32% and burned areas are projected to increase by 59±33% by 2040 in the Sierra Nevada (Gutierrez et al., 2021). However, there has also been a shift in where and when fires burn and how fast fires grow. Statewide, there has been an increase in fires during the early spring and late fall since 1982 (Xu et al., 2022). There has also been a pronounced shift toward higher elevation forests burning, particularly in the Sierra Nevada. Historically, the annual burned areas were predominantly confined to shrublands. However, since 2002, most of the annual burned areas have been in forests, with a fourfold increase in burned areas in high elevation forests since 2008 (Xu et al., 2022) that is strongly aligned with model projections of increasing high elevation wildfires (Alizadeh et al., 2021; Li & Banerjee, 2021; AghaKouchak et al., 2018; Westerling et al., 2018). Finally, fast growing wildfires, which account for most structural destruction and suppression costs, have more than doubled their daily growth rate since 2000 (Balch et al., 2024).

Drought

Drought (defined as a deficit in water availability relative to the long-term average) will strongly impact the Sierra Nevada in the 21st century. The massive ecological consequences alone, aside from the social and economic impacts, of the 2012–2016 California drought provide a clear example of how climate change-fueled drought will spark episodes of rapid and widespread ecological change across the Sierra Nevada. 2000–2018 was the driest 19-year period since at least 800 C.E. and over 40% of the increase was driven by the anthropogenic warming and drying trends to date (Williams et al., 2020). Given the grim warming, drying, and snowpack trends outlined in Chapter 2, these sorts of extreme droughts, where natural variability is exacerbated by anthropogenic climate change to exceed historical precedents, can be viewed as a main driver of ecological change in the Sierra Nevada region over the coming decades. Drought poses a

particular threat to forests (see Forests in *Section 3.1.3 Vulnerability*) but will likely be an overriding dominant driver of ecological change in all ecosystems in the Sierra Nevada. Moreover, drought strongly increases wildfire risk by decreasing the moisture in live fuels, directly increasing downed woody debris, and interacting with other causes of tree mortality, such as insects to alter fuel conditions and forest structure.

Carbon Storage and Biophysical Climate Feedbacks

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 an average of 9.5 million metric tons (MMT) of carbon dioxide equivalents per year from the atmosphere (Christensen et al., 2017). There has recently been a strong increase in interest in forest conservation for the purpose of nature-based climate solutions leveraging forests for their carbon sequestration potential to combat climate change. However, to be an effective climate solution, nature-based solutions must be durable to carbon losses due to disturbance, and must provide additional carbon sequestration over some alternative or counterfactual scenario (usually relative to the forest project not being protected), among other key criteria (Anderegg et al., 2020). By its very nature, climate change is making it increasingly unlikely to expect *permanence* (i.e., decades-to-century scale carbon storage in Sierra forest projects) as most projections indicate net carbon losses from California forest ecosystems (**Figure 3.3**) and no current nature-based solution project in California has yet to demonstrate clear additionality (meaning that the forest ecosystems end up storing more carbon than what would have been stored under existing management practices) in independent scientific assessments (Coffield et al., 2023). There is also likely a strong trade-off between the dual management goals of maximizing carbon storage in natural landscapes and maximizing the fire and climate resilience of these same landscapes (Guo et al., 2025).

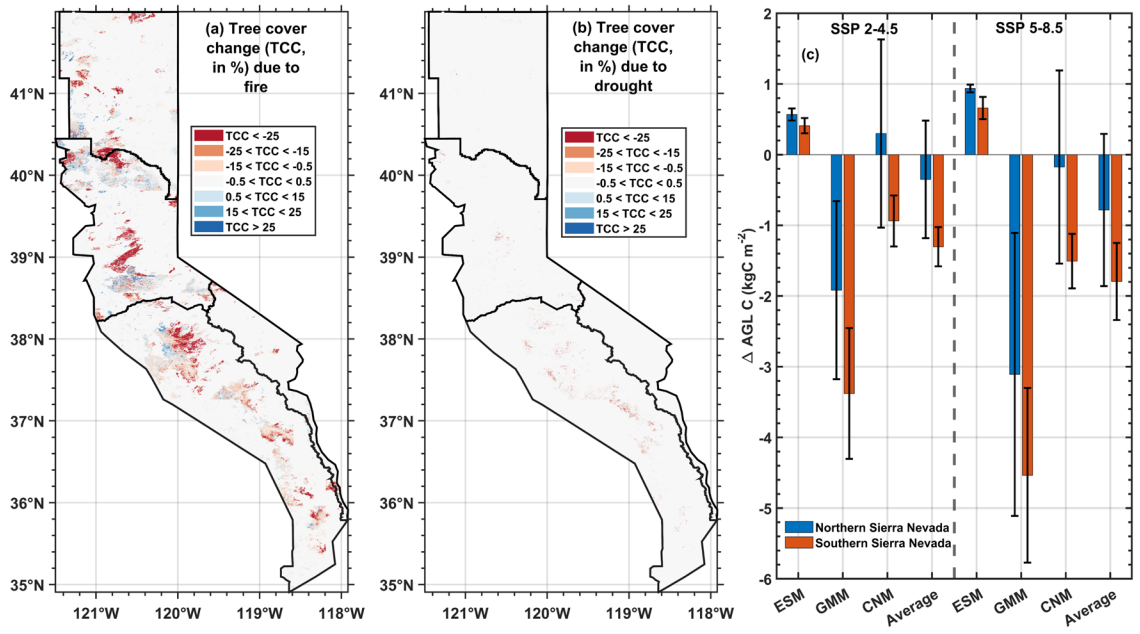


Figure 3.3: *Percent change in tree cover change (TCC) over the historical period from 1985–2021 due to (a) wildfire and (b) drought. Red colors correspond to tree cover loss and blue colors correspond to tree cover increases (Data source: Wang et al., 2022). (c) Projected changes in aboveground live carbon (AGL C) for 2081–2100 for the Northern (blue) and Southern (red) Sierra Nevada using three separate ecological forecasting tools including an ensemble of coupled climate Earth system models from the Coupled Model Intercomparison Project Phase 5 (ESM), a demographic growth-mortality model (GMM) derived from Wu et al. (2023), and an ecological climate niche model (CNM). The climate change scenarios are the SSP 2–4.5 (intermediate) and SSP 5–8.5 (worst-case). Corresponding values were not available for SSP 3–7.0. Negative values correspond to projected carbon losses.*

While they cover a smaller fraction of the geographic land area of the Sierra Nevada, ecosystems that sequester and store carbon belowground (e.g., wet meadows, fens, and grasslands) may become increasingly important under climate change. Wet meadows cover less than 3% of the geographic land area but may contain 12–30% of soil carbon stocks (Norton et al., 2014, 2011), with the ability to sequester three to six times as much carbon, per unit area, as the surrounding forest (Reed et al., 2021). Sierra Nevada meadows also have large amounts of carbon stabilized by association with mineral soil particles relative to other ecosystems (Reed et al., 2026). This mineral association, coupled with high rates of vegetative carbon inputs, allows carbon to persist for hundreds to thousands of years in these ecosystems (Reed et al., 2026). However, many meadows in the Sierra Nevada have been impacted by anthropogenic activities (e.g., livestock grazing and construction of roads), incision and forest encroachment, and the loss of beaver that have decreased ecosystem resilience and converted them from net carbon sinks to carbon sources for the atmosphere (Reed et al., 2021). Restoration of floodplain hydrology and reintroduction of beavers has been shown to stem carbon losses, re-establish conditions for soil carbon sequestration, and increase the long-term persistence of carbon in meadows (Reed et al., 2026; Bagcilar et al., 2024; Morra et al., 2023; Reed et al., 2022; Wohl et al., 2013). Some uncertainty remains around the durability of meadow carbon under changing climate conditions (Arnold et al., 2014), as the surrounding forests continue to exploit deeper groundwater due to loss of mountain snowpack and enhanced evapotranspiration (Klos et al., 2023; Guo et al., 2022). However, as rates of carbon sequestration and mineral association are driven by vegetative productivity (Morra et

al., 2023; Reed et al., 2021), meadows with undisturbed or restored hydrology that can maintain sufficient moisture may also see increased rates of carbon sequestration under climate change (Jiang et al., 2024; He et al., 2024).

UNCERTAINTIES

Beyond the climatological uncertainties about the pace and magnitude of temperature and hydrological changes (i.e., which model scenario in Chapter 2 will most closely resemble our three emissions pathway, within scenario uncertainty) for Sierra Nevada ecosystems, there are key ecological uncertainties around the pace and scale of fire- and drought-driven disturbance; the extent of geographic range shifts of species of concern; new behaviors of native pathogens and insects (e.g., bark beetles) in novel climates and the emergence of novel pathogens or insects (Trugman et al., 2021); the role of microclimate and complex hydrology in decoupling local responses from regional trends (e.g., **Box 2.1**); and the uncertainty in climate change scenario and impact projections (Guo et al., 2022). While the general pattern of increasing wildfire and drought-induced forest mortality suggests widespread decreases in forest cover and carbon storage across the Sierra Nevada region, the local specifics remain difficult to predict (**Figure 3.2**). In particular, the trajectory of post-disturbance recovery and likelihood of returning to conifer forests, broadleaf forests, persistent shrublands, meadows, or grasslands remain difficult to forecast in many regions (Guiterman et al., 2022) because historical analogs become increasingly uninformative as climate surpasses the range of historical variability. Thus, predicting when and where type conversion will occur, and identifying management actions that can alter its trajectory remain key priorities for the Sierra Nevada (Povak et al., 2024).

Significant progress has been made in understanding individual drivers of wildfire such as drought, heat waves, and fuel accumulation, but major gaps persist in linking compounding extremes, ecosystem feedbacks, and management responses. Compound events such as drought, combined with heat waves, pest outbreaks, and post-fire regeneration failure, interact to amplify wildfire occurrence, severity, and ecosystem transitions. For example, studies have documented nonlinear increases in burned areas under extreme temperature events in the Sierra Nevada (Gutierrez et al., 2021), while global analyses show that compound hot-dry extremes are intensifying, increasing fire weather risk (Fan et al., 2023).

Anticipating thresholds at which forests shift to shrub or grass states, particularly in mid-elevation zones, requires more integrated process understanding and models. Although current systems monitor burn severity well, they do not adequately track post-fire ecosystem trajectories, including vegetation regrowth, soil carbon losses, erosion, hydrologic change, and mortality carryover effects. Recent work in Sierra basins has quantified how reintroducing wildfire influences aboveground carbon dynamics, underscoring the need to assess net carbon balance under active fire regimes (Nesbit et al., 2025). Remote sensing studies reveal shifts in evapotranspiration following fire, but field-based data and coupled carbon-water models remain limited (Ma et al., 2020). The accelerating decline of Sierra Nevada snowpack and earlier melt may intensify vegetation water stress and prolong fire seasons, yet research is sparse on how changing snow–rain proportions affect fuel moisture, evapotranspiration, and fire behavior. Feedbacks between hydrologic stress, vegetation mortality, and fire susceptibility remain a major uncertainty.

The abilities of monitoring networks, in collaboration with universities, state agencies, nonprofit science groups, and Tribes, to track fine-scale fuel moisture, soil and canopy microclimate, and post-fire physiological stress are also limited. Expanding flux towers, dendrometer networks, field plots, and sensor arrays would generate high-resolution data to validate remote sensing and strengthen predictive fire models, while also enabling early-warning capacity. The social vulnerability of Tribal people and other communities to wildfire and smoke exposure in Sierra Nevada is understudied, and better data are needed to evaluate trade-offs between prescribed burning, mechanical thinning, and uncontrolled wildfire for public health, air quality, and equity. Weaving western science and Tribal Knowledges, addressing capacity constraints, and ensuring equitable access to adaptation resources are essential. Finally, despite substantial investments in thinning, prescribed fire, and ecosystem restoration, landscape-scale effectiveness under future climate remains uncertain. Current fuel treatments cover only a small fraction of the area needed to significantly alter fire dynamics (North et al., 2024). Adaptive experiments that combine field trials, remote sensing, and modeling are required to evaluate how management portfolios influence fire behavior, carbon, water, and biodiversity over long timeframes.

Geographic range shifts are a classic ecological fingerprint of climate change (Moritz et al., 2008; Root et al., 2003) yet remain extremely difficult to predict (Bessinger & Riddell, 2021; Anderegg & HilleRisLambers, 2019), particularly for range expansions (Gilbert et al., 2024; Angert et al., 2011). The ability of both species of concern and keystone species to shift their geographic distributions under a changing climate remains variable in the Sierra Nevada. Relatedly, the emergence of native pathogens or insects as unexpectedly epidemic rather than endemic mortality agents (e.g., Dendroctinus species during the 2012–2016 drought, Trugman et al., 2021; Stephenson et al., 2019), or climate-facilitated spread of invasive species (e.g., spread of gold spotted oak borer outside of Southern California, Venette et al., 2015), present large but difficult to quantify risks. Both of these *known unknowns* require additional study and ongoing, data-driven adaptive management (*Section 3.1.4 Adaptation Actions*).

Further, the extreme topographic, geologic and hydrologic complexity of the Sierra Nevada makes it difficult to scale down regional trends in climate and resource availability to finer scale outcomes (Lundquist & Cayan, 2007). For example, areas of giant sequoia persistence tend to be in moist edaphic conditions that are not generally resolved in broader scale climate products used to develop estimates of ecological risk. This mismatch in our scale of understanding and the actual environmental conditions experienced by the ecosystems makes it difficult to anticipate climate risks. Following this example, sequoia mortality in the extreme 2012–2016 California drought was remarkably low compared to other tree species, likely because sequoias exist only in areas with substantial subsurface water supply that was evidently not impacted to the extent that upland forest counterparts experienced (Stephenson et al., 2018). Another example is the fine-scale distribution of tree recruitment to maintain forest and woodland vegetation types. The ecologically relevant temperature for seedling establishment can vary up to 10°C (18°F) from 2-meter air temperature depending on orographic effects and canopy cover (Davis et al., 2019; Davis et al., 2016b), driving large uncertainty in forest regeneration across the topographically complex Sierra Nevada, particularly after disturbance-driven changes in canopy cover (Wolf et al., 2021; Brown et al., 2014). Finally, for longer scale projections (i.e., decades to a century), there is significant uncertainty in the level of human emissions and subsequent level of climate change and in how the physiological effects of CO_2 fertilization on plants, which can increase plant carbon assimilation

and biomass, will interact with the inevitable increases in drought and wildfire to ultimately impact ecosystem biomass and resilience (Guo et al., 2022; Swann et al., 2018). **Figure 3.3** highlights these uncertainties, where ecological model projections at the end of the century range from *moderate increases* in carbon for the Sierra Nevada in coupled climate Earth system models—that include a mechanistic representation of the physiological effect of CO_2 on plant biomass gain, but lack some of the key processes associated with drought- and fire-driven mortality)—to *strong decreases* in carbon and tree cover in models that have a more careful representation of climate impacts on tree mortality, but do not include a mechanistic representation of the physiological effect of elevated CO_2 on plant health status.

3.1.2 Climate Effects, Trends, and Projections for Biodiversity

CLIMATE EFFECTS

Climate change affects the Sierra Nevada region's wildlife in direct and indirect ways, both physiologically and through myriad ecological interactions. Species are likely to be physiologically affected by climate change through changes in metabolic and growth rates, altered reproductive output, and changes in the frequency of heat stress or cold-related injuries or mortality (Huey & Kingsolver, 2019; Kingsolver et al., 2013; Savage et al., 2004). The indirect effects of climate change are more numerous, pervasive, and variable. Climate change will alter plant species distributions, plant communities, and in turn, habitat for many species. Climate-induced changes in fire and hydrologic regimes will have additional effects on habitat, food resources, and hence, reproduction and mortality rates of many species. Climate change will also alter interspecific interactions, potentially changing predator-prey dynamics, competitive relationships, the effects of parasites and diseases, and facilitative interactions (HilleRisLambers et al., 2013). In addition, many wildlife species will likely be affected by other non-climatic stressors that are driven by climate change. For example, many invasive species are expected to benefit from climate change, potentially resulting in increased negative effects on native species (Dukes & Mooney, 1999). There may also be more subtle effects of climate change on wildlife including increases in human-wildlife interactions as people change their behavior. Much of the content in this report so far provides an overview of the climate-induced changes wildlife species and their habitats will be exposed to. The other components of vulnerability for wildlife—sensitivity and adaptive capacity—are summarized below.

Sensitivity is a measure of how much climate-driven change a species can tolerate. For any species, sensitivity is a function of many factors including physiology, life history traits, and trophic and competitive relationships. For example, endotherms tend to be more tolerant and successful under a wider range of temperatures than ectotherms. Endotherms can modify hair or feathers seasonally and can expend energy to warm. Ectotherms have no ability to regulate their body temperatures through metabolic processes; they are limited to seeking appropriate temperatures for thermoregulation. Aquatic organisms are more sensitive to adverse temperatures than terrestrial organisms because water conducts heat efficiently and they cannot avoid overheating when water temperatures increase, unless locally cooler water is available (Leathers et al., 2022). Specialist species (i.e., stricter habitat or food requirements) will also likely be more sensitive to climate change than generalist species that can utilize a wider variety of environments and food resources without impacting their survival and reproduction (Colles et al., 2009).

Adaptive capacity refers to a species' or ecosystem's ability to adjust and respond to changing environmental conditions while maintaining functional stability. The two defining factors of adaptive capacity for wildlife can be understood as inherent or contextual/external. As with plants and fungi, inherent adaptive capacity for animals is determined by dispersal ability, phenotypic plasticity, and evolutionary capacity. Dispersal ability refers to a species' ability to track changing conditions over time. This is largely dependent on a species' mobility throughout its life stages, with less mobile species facing more challenges in keeping pace with environmental change. However, the mere ability of highly mobile species to track their climate niches may not save them if the resources they depend on, such as host plants, are less mobile and hence unavailable with significant time lags. Phenotypic plasticity refers to the ability to change behavior or morphology in response to changing conditions. For example, migrant wildlife (e.g., mule deer) exhibit plasticity in the timing of their migration in response to local climatic conditions and plant phenology, which should help them track climate-driven temporal changes in resource availability for essential and historical life cycles (Monteith et al., 2011). This contrasts with long-distance migrant wildlife, such as some bird species, who do not receive local cues to inform the timing of their migration and instead rely on evolutionary mechanisms to keep pace (Seavy et al., 2009; MacMynowski & Root, 2007). Such mechanisms are in the realm of evolutionary capacity, which refers to the ability to evolve in the face of climate change. Contextual, or external, aspects of adaptive capacity include landscape patterns and conditions that facilitate or serve as barriers to movement that impact survival and dispersal (e.g., local microrefugia that can mitigate the effects of extreme heat events), as well as the capacity of managers to improve the ability of species or habitats to adapt to climate change (e.g., forest treatments that reduce the likelihood of large-scale habitat loss from high-severity fire).

CLIMATE TRENDS AND PROJECTIONS

Climate change is already impacting Sierra Nevada wildlife and is projected to have larger effects as global temperatures continue to rise. Thermal impacts due to increasing temperatures have been hypothesized and observed, with both positive and negative effects projected for a variety of wildlife in the Sierra Nevada, depending on the species and context. In simulations for several major streams throughout the region under climate change, stream temperature-driven changes in aquatic environments (e.g., dissolved oxygen) surpassed survival thresholds for several aquatic indicator species, with cold water restricted to higher elevations and groundwater-dominated basins where temperatures are predicted to remain within thermal tolerances (Ficklin et al., 2013; Null et al., 2013).

The direct effects of temperature on terrestrial organisms of the Sierra Nevada are generally not well studied. Rowe et al. (2015) supported the upslope migration hypothesis for montane mammals but documented varying responses by species across the landscapes. For example, negative direct effects of warming temperatures have been hypothesized for American pika (Ochotona princeps) (Stewart et al., 2017, 2015); however, the talus and broken rock substrates which they inhabit have a unique ventilation process that keep interiors cool in summer and warm in winter, decoupling them from external climate in the region (Millar et al., 2014, 2013). Consequently, recent studies have shown no impact of climate on pika population dynamics in the Sierra Nevada (Smith et al., 2024; Millar & Smith, 2022). In contrast, warming temperatures could benefit ectothermic terrestrial invertebrates at some parts of the year (Forister et al., 2018). Most

effects of rising temperatures on terrestrial endotherms are expected to be indirect. For birds, the effects of warming temperatures appear mixed and species-dependent. Jones et al. (2016a) found that warmer summer temperatures negatively affect the predicted occupancy by the California spotted owl (Strix occidentalis occidentalis), but dense closed-canopy forests create microclimates that can buffer against this effect. Roberts et al. (2019) found that of 45 bird species analyzed in the Southern Sierra, 47% had an increase in biomass, whereas 27% had a decrease, during higher temperature years (2010–2016). In Yosemite, productivity of several bird species was positively associated with warmer spring temperatures from 1993–2017 (Saracco et al., 2019).

Shifts in species' ranges or distributions are expected to occur where climate change alters population growth (i.e., rates of survival and reproduction) unevenly across a species' range. For example, populations may decrease where habitat conditions deteriorate along one edge of the species' distribution (e.g., at lower latitudes and elevations), and/or populations may increase where conditions improve (e.g., higher latitudes and elevations). 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, 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 (i.e., 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). Tingley et al. (2009) researched 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. 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 non-ruderal species, as well as increased abundance at higher elevation sites. High-alpine specialist species, however, declined or were stable.

Because of the topographic shape of the Sierra Nevada, with most of the land area at middle elevations (Elsen & Tingley, 2015), species occurring at lower elevations that shift their ranges upward in elevation may undergo range expansions before potentially contracting again at higher elevation. However, projected range expansion due to climate change may be partially or entirely canceled by land-use change, as is projected for the birds of oak woodlands in the Sierra Nevada foothills (Jongsomjit et al., 2013).

Changes to the fire regime are likely to profoundly alter wildlife habitat, with the potential for large-scale displacement and range shifts. Historically, mixed severity fire supported a diversity of successional stages and habitat types across forested landscapes, which in turn supported high biodiversity (Steel et al., 2019; Tingley et al., 2016). As the diversity of successional stages is homogenized with increasingly large and severe fires, we would expect some measures of biodiversity to decrease at some point. Species associated with mature forests are already experiencing large-scale habitat loss from the increased severity and extent of wildfires (Hart et al., 2025; Steel et al., 2023; Jones et al., 2016b), with habitat loss projected to increase. Increasing fire frequency and size is also a threat to the fauna of the sagebrush ecosystem of the eastern Sierra and Modoc Plateau (Doherty et al., 2022; Coates et al. 2016). For example, fire is considered the primary threat to the Bi-State Distinct Population Segment (DPS) of the greater sage-grouse

(*Centrocercus urophasianus*), with an increase in its habitat loss due to fire from 11,083 acres in 1990–2000 to 73,791 acres in 2010–2020 (Bi-State Action Plan, 2025).

Conversely, species that have adapted to fire disturbance and early- and mid-seral habitats may find a Sierra Nevada landscape increasingly suitable for them. Several wildlife species, including some pollinators, bats, and birds, have positive relationships with moderate- and high-severity fires (Tarbill et al., 2023; Steel et al., 2019; Taillie et al., 2018). It is likely that many of these species will become more abundant. For example, Rousseau et al. (2025) found that populations of Hairy Woodpeckers, which are associated with disturbance and post-fire conditions (Campos et al., 2020; Roberts et al., 2019), increased by 98% from 2010–2024, according to a Sierra-wide monitoring dataset, as fires burned 33% of their sample locations over that same period.

Yet, even species positively associated with high burn severity may increasingly find post-fire habitats unsuitable for them. Wildlife that is dependent on abundant fire-killed conifer snags, for example, require mature live trees available to be fire-killed (e.g., Campos et al., 2020), which will not be available post-fire if the frequency of fire outpaces their ability to grow sufficiently between fires. For some birds that prefer to nest in complex, early-seral forests within high-severity burn patches, the patches toward the centers can become too large to be suitable habitats (Steel et al., 2022; Stillman et al., 2019).

The projected changes to hydrologic regimes will also alter habitat suitability for Sierra Nevada wildlife through higher peak flows, temporal shifts in the hydrograph, lower flows and potential drying of aquatic habitats during drought, and increased sedimentation (Ficklin et al., 2013; Null et al., 2013). Montane and Great Basin lakes fed by Sierra Nevada runoff are experiencing drier and warmer conditions (Smits et al., 2021; Streib et al., 2021). Declining lake levels and increased salinity have been observed (Herbst, 2023; Haig et al., 2019), largely driven by stream diversions for municipal and agricultural uses, with climate change acting as an additional stressor. Continued drying of saline lakes will significantly impact habitat and food chains (Haig et al., 2019). For example, alkali fly (*Ephydra hians*) and brine shrimp (*Artemia spp.*) are key food sources for breeding migratory water birds (Herbst, 2023; Wrege et al., 2006). Kutsavi, larvae and pupae of the alkali fly is also an important part of Kucadikadi people's diet (Mono Lake Committee, n.d.). In post-fire watersheds, high-peak flows increase the likelihood of high inputs of ash into waterways which can kill 20–33% of chinook salmon yearlings within hours of exposure at high concentrations (Kwan et al., 2024). Kiernan and Moyle (2012) used a long-term dataset to study the impacts of environmental changes on fish communities in Martis Creek and found that the proportion of introduced species increased in years with low annual streamflow, but that these species were also more susceptible to winter and spring high-flow events, suggesting that native fish assemblages may be better able to persist under changing hydrologic conditions. Lower down the food chain, invertebrate communities in headwater streams may also have some resilience to high-flow events when not subjected to other sources of degradation disturbance such as livestock grazing (Herbst & Cooper, 2010), but may be less resilient and resistant to intensifying, long-term drought (Herbst et al., 2019). Leathers et al. (2024) found that invertebrate communities are also sensitive to shifts in the hydrograph: early snowmelt in the Eastern Sierra streams destabilized the streams' epilithic biofilm metabolisms and altered key ecosystem functions such as insect production and emergence through shifts in community composition, structure, and phenology.

While species with fully aquatic wildlife are perhaps the most obviously sensitive to changes in hydrologic regimes, semi-terrestrial and fully terrestrial species are not spared. Several amphibian species in the Sierra Nevada are highly sensitive to changes in precipitation amount and type because of their reliance on water for breeding, thermoregulation, and movement, with snowpack playing a particularly important role. Higher snowpack is generally associated with increased reproduction (Brown et al., 2012; Lacan et al., 2008) due to greater spring water availability and reduced drying of small ponds in summer, which is especially critical for species that remain in aquatic life stages for 1–3 years before metamorphosing into froglets (Halstead et al., 2023). Snowpack may also influence colonization dynamics. April snowpack has been found to either increase or decrease colonization probability, depending on the amphibian species (Halstead et al., 2023). As for fully terrestrial wildlife, many species depend on deep snowpack to insulate the ground surface and soil from deep freezing (Edwards et al., 2007; Groffman et al., 2001). At high elevation habitats in the central Sierras near Donner Pass, reduced snowpack caused by warm winter temperatures were strongly negatively correlated with butterfly density in the subsequent year, likely because of direct mortality of overwintering eggs and early instar larvae (Halsch et al., 2024). Some bird species alternatively may benefit from reductions in snowpack. Years of less snow accumulation and early snowmelt in the Sierra Nevada, especially at high elevations, were associated with higher species richness, more breeding territories, population increases, earlier fledging, and higher productivity of many bird species at subalpine and montane elevations (DeSante & Saracco, 2021; Saracco et al., 2019; Morton, 2002; Morton et al., 1972).

The Sierra Nevada is a strongly seasonally pulsed system. As such, many animals, including insects, fish, amphibians, birds, and ungulates, time their developmental stages (i.e., emergence, breeding, and migration) around snow disappearance, plant green-up, and flowering, and exhibit plasticity in the timing of these events. To avoid discrepancies with essential and historical life cycles, wildlife will need to track accelerating shifts in the timing of seasonal resource availability for continued successful breeding and survival. Resident species and short-distance and altitudinal migrants are thought to be more capable of adjustments to timing given the availability of local cues, while long-distance migrants are more prone to incompatibility given their reliance on slower evolutionary mechanisms for adaptation (MacMynowski & Root, 2007). Many bird species in Yosemite have shown resilience to phenological shifts thus far, with the community advancing their breeding phenology by 0.2 day/year and productivity increasing by 0.8%/year from 1993–2017 (Saracco et al., 2019). However, continued warming may alter these relationships in the future.

3.1.3 Vulnerability

FORESTS

Over the past several decades Sierra Nevada forest ecosystems have been strongly impacted by escalating wildfire, drought, and insects and pathogen disturbance, highlighting key areas of vulnerability to climate change. The major drought from 2012–2016 resulted in the death of millions of trees and increased background mortality rates (Van Mantgem et al., 2009). In many cases, while drought triggered tree stress, the ultimate cause of mortality was due to bark beetles that killed wide swaths of trees not only in the Sierra Nevada (Das et al., 2016), but across the western United states from New Mexico to Canada (Kurz et al., 2008). Projected decreases in

snowpack, increased temperature, and changes in the intensity and distribution of precipitation will only exacerbate future drought mortality trends and other co-occurring forest disturbances. On the wildfire front, recent decades have seen an exponential increase in tree cover loss to wildfire totaling 5,000 km^2 across the State of California since 2000, a large portion of which is in the Sierra Nevada region (Wang et al., 2022). Wildfire trends are projected to strongly increase with climate change even under modest emissions scenarios (Wu et al., 2023). Even forest ecosystems that are typically fire-adapted have recently suffered losses from extreme fire and drought. For example, the recent 2021 Kings Canyon and Sequoia National Park (KNP) and 2020 Sequoia National Forest (SQF) Complex fires resulted in losses of 13–19% of the world's giant sequoia (*Sequoiadendron giganteum*) population (Soderberg et al., 2024; Stephenson & Brigham, 2021). Changing climate conditions and increased drought also open up forest systems to increased insect and pathogen disturbance of known mortality drivers such as the mountain pine beetles (Stephenson et al., 2019; Kurz et al., 2008) and novel insects (or *unknown unknowns*) that could drastically impact ecosystem structure and function but are currently impossible to assess given the nature of the threat (Trugman et al., 2021). With forest losses after disturbance, there has already been observed to be increased type conversion due to regeneration failure. Indeed, shrublands and grasslands have already been documented to have increased at the cost of forest area by ~4,000 km^2 in the State of California since the year 2000 (Wang et al., 2022).

OAK WOODLANDS

Oak woodlands are already strongly affected by livestock grazing and land conversion, and are increasingly impacted by wildfire, drought, and biotic agents. Livestock grazing can change fire behavior by reducing fuel loads, but it also alters understory plant communities, and potentially reduces seedling and sapling recruitment of oak species (Davis et al., 2011). This recruitment limitation may be particularly important for deciduous oaks such as blue oak (*Quercus douglasii*) and valley oak (*Quercus lobata*), which have shown limited regeneration in parts of their range (Zavaleta et al., 2007; Tyler et al., 2006; McClaran & Bartolome, 1989; Duncan et al., 1987) and can be hurt by heavy summer grazing pressure (McGreary et al., 2005). Conversion of oak woodlands for agricultural, urban, and residential uses impacts oak woodlands through direct removal and fragmentation (Davis et al., 2016a). The California Department of Finance projects that California's human population will increase to approximately 40.9 million by 2040, further threatening oak woodlands of the Sierra Nevada foothills with urban expansion. Outside of human development, 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 as the climate warms (Kueppers et al., 2005). The direct climate impact on oak woodlands is likely centered around drought-induced mortality of adult oak trees, which was substantial during the 2012–2015 drought, though less than for many Sierra conifers (McLaughlin et al., 2020; Das et al., 2019). It will also be accompanied by increasingly limited climatic windows for recruitment (Davis et al., 2016b). 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 because of a continued increase in high-severity fires, increased precipitation and higher temperatures, and nutrient inputs from air pollution (Lenihan et al., 2008; 2003; North et al., 2016). Densities of Sierra Nevada montane hardwood stands have increased by 100% in plots compared from 1930–2000, more

than any other forest type in plots compared during this timeframe, with the proportion of plots dominated by hardwoods increasing by 100% (Dolanc et al., 2014). During the 2012–2016 drought, black oaks had among the highest survivorship of any tree species studied (Pile et al., 2018). Indeed, paleoecological evidence suggests that oaks tend to replace pines as the dominant genus of California tree in warmer periods with increased fire prevalence (Mensing, 2015), suggesting that a spread of montane oaks may ultimately be climate adaptive in order to avoid forest and woodland conversion to shrublands or grasslands.

SHRUBLANDS

Sierra shrublands fill enormously varied geographic and ecological niches in the region ranging from chaparral on the western foothills to sage scrub across much of the eastern Sierras to alpine dwarf-shrublands at high elevations. Lower elevation shrublands are drastically increasing in abundance, particularly as the result of vegetation type conversion after high-severity fire (Guiterman et al., 2022; Steele et al., 2022). Historically, many of these shrublands (e.g., montane chaparral) were early-seral cover types or restricted to steep, south-facing slopes with poor soil. However, it remains unclear whether the extensive forest to shrub conversion seen in the Southern Sierra Nevada in the past decade (Steel et al., 2022) will recover to forests or woodlands in the following decades, or transition to semi-permanent shrubland. Though low elevation shrublands are increasing in extent, they are also vulnerable to invasion from nonnative grasses such as cheatgrass, which further increase ecosystem wildfire vulnerability and can accelerate type conversion from shrubland to extensive areas of non-native grassland. Regardless, the ecosystem dynamics and functions (e.g., carbon storage) of foothill and montane shrublands are less well studied than most other vegetation types and will likely become increasingly significant to the ecology of the region over the next century. Meanwhile, high-elevation dwarf-shrubs may have important microclimatic buffering potential against warming for alpine ecosystems (Galle et al., 2024), but it remains difficult to project whether they will experience more benefit from near-term climate change due to a longer growing season (Franklin, 2012), or become vulnerable to a drier hydroclimate and invasion from subalpine species.

RIPARIAN AND AQUATIC ECOSYSTEMS

Riparian and aquatic ecosystems are highly sensitive to stressors that alter local and regional hydrologic regimes. High rates of anthropogenic disturbance in these ecosystems further result in loss of ecological integrity and decreased resilience. Meadows and fens throughout the Sierra Nevada region have been heavily impacted by beaver extirpation, grazing, ditching, road construction, and logging since the mid–1800s and, as a result, the majority of those ecosystems may have been degraded or lost (Lanman et al., 2012; Menke et al., 1996; Burcham, 1981). These disturbances often result in stream channel incision that leads to increased depth to groundwater, decreased groundwater recharge, lower vegetative productivity, and reduced habitat value (Essaid & Hill, 2014; Loheide & Gorelick, 2007; Toledo & Kauffman, 2001). Aquatic ecosystems are some of the most imperiled habitats in the Sierra Nevada and most have experienced loss of biotic integrity because of large dams, introduced fish, and human land use (Moyle & Randall, 1998). Projected changes in the timing, form, and amount of precipitation that are expected to lead to earlier peak runoff and decreased summer flows are also likely to alter abiotic processes and increase stress on biotic systems, particularly in ecosystems already imperiled by

human disturbance (Yarnell et al., 2010; Milly et al., 2008; Jager et al., 1999). Increasing stream temperatures may also cause dissolved oxygen concentrations to drop below levels needed to maintain aquatic ecosystems, especially in lower elevation subbasins (Ficklin et al., 2013). Watersheds at high elevations, with larger groundwater reservoirs, and in areas less dependent on snowmelt may be less vulnerable to changes in precipitation timing, or to transitions from snow- to rain-dominated precipitation regimes (Null et al., 2010).

Projected increases in the duration and intensity of droughts are likely to increase stress to aquatic and riparian ecosystems. Drier soil conditions and the subsequent loss of wetland vegetation are likely to increase their susceptibility to erosion and conifer encroachment, particularly in ecosystems with altered hydrology (Lubetkin et al., 2017; Loheide & Gorelick, 2007; Toledo & Kauffman, 2001). Drought-driven variation in stream conditions may also impact biotic assemblages and invasion of non-native species (Leathers et al., 2025; Herbst et al., 2019; Kiernan & Moyle, 2012). Meadows and riparian areas with hydrologically connected floodplains that support groundwater recharge and dense cover of herbaceous wetland species are likely to be less vulnerable to erosion, are better equipped to buffer the effects of extreme climate events, and continue to provide critical refugia for aquatic species (Lucas et al., 2016; Tague et al., 2008; Micheli & Kirchner 2002). However, ephemeral streams and wetlands, or those with impacted hydrology, may experience altered ecosystem function, reduced habitat value, and even type conversion to upland vegetation by the end of the century (Lubetkin et al., 2017; Lee et al., 2015).

Increased frequency and severity of wildfire may have complex and contrasting effects on riparian and aquatic ecosystems depending on ecosystem condition, fire severity, and precipitation patterns. In general, riparian and aquatic ecosystems are relatively unaffected by fire (Fairfax & Whittle, 2020) and may provide valuable refugia for wildlife (Jager et al., 2021). However, over a century of fire suppression has contributed to widespread encroachment of meadows and riparian areas by conifers and shrubs (Cummings et al., 2023). This encroachment of upland species, combined with drying of riparian soils as a result of hydrologic alteration compounded by drought, may increase the susceptibility of these ecosystems to fire. At the same time, loss of upland vegetation following wildfire, and corresponding decreases in rates of evapotranspiration, may lead to elevated water tables in hydrologically connected meadows and reconversion of encroached areas to riparian vegetation (Boisramé et al., 2017; Wood, 1975). Projected increases in intense fires are also likely to increase levels of suspended sediment and alter stream chemistry, particularly when followed by extreme precipitation events, with negative implications for aquatic organisms (Santos et al., 2019; Verkaik et al., 2013; Gresswell, 1999).

WILDLIFE

While climate-driven changes to wildlife and their habitats will likely be pervasive across the region, a few groups of species stand out as particularly vulnerable. These include species restricted to high-alpine environments, species that are dependent on snowpack for key stages of their life cycles, species associated with mature forests, and fully aquatic species dependent on cold water (<22°C or 72°F). True mountaintop species associated with high-alpine habitats (e.g., Sierra Nevada red fox (*Vulpes vulpes necator*) and Sierra Nevada bighorn sheep (*Ovis canadensis sierrae*) cannot move up in response to warming conditions (SNRFCAT, 2022; USFWS, 2007). For wildlife that depend on the subnivean environment, or who have specific physical or phenological

adaptations to snow, reduced snowpack represents a loss of critical habitat (e.g., Halsch et al., 2024). These snowpack-dependent species have yet to be enumerated, but include invertebrates, fishes, amphibians, and mammals, some of which are discussed above. Lastly, because mature forests are already diminishing at alarming rates, and are projected to decline more rapidly with continued climate change, these species are also likely highly vulnerable. For example, between 2011–2022, during a period of widespread forest mortality from wildfire and drought, 50% of mature forest habitats and 85% of high-density mature forests in the Southern Sierra Nevada either transitioned to lower density forests or non-forest vegetation types (Steel et al., 2023). As a result, Pacific fisher habitat declined by 48% and canopy cover of California spotted owl protected activity centers declined by 49% (Hart et al., 2025; Steel et al., 2023). Finally, a climate change vulnerability assessment by Moyle et al. (2013) found that most native fishes in California will suffer population declines and become more restricted in their distributions, with fishes that require cold water (<22°C or 72°F) being particularly vulnerable to extinction. This vulnerability likely extends to other fully aquatic organisms that depend on cold water in the Sierra Nevada.

Table 3.1: *Summary of Key Vulnerabilities Across Systems in the Sierra Nevada, with Localized Context and Confidence in Attribution*

Category	Vulnerability	Evidence (Observed & Projected)	Localized Context	Attribution Confidence
Hydrological	Snowpack loss and increasing rain-on-snow events	The historical April 1 SWE has declined across most of the region. Projections indicate up to ~90% loss across ~35% and ~60% of the currently snow-covered areas of the Sierra Nevada by end-century under high and worst-case scenarios, respectively. Rising snowlines (~1500–3000 ft) increase the proportion of precipitation falling as rain and the frequency of rain-on-snow events.	Northeastern, Northern, Southeastern, and Southern Sierra Nevada subregions; Sierra Nevada headwater watersheds	Very High
Hydrological	Seasonal redistribution of runoff and lower flows during the summer	Winter runoff increases (as much as 37% in Southeastern Sierra) while summer runoff declines by as much as 41% (high emission) and 32% (worst-case emission) of the historical values in Northern Sierra Nevada by end-century. Annual totals remain relatively stable (~88–121% of historical levels).	Northern and Southern Sierra Nevada; mid-elevation watersheds; Sierra Nevada headwaters	High (timing); Medium (annual totals)
Hydrological	Soil moisture drying and recharge stress	Summer soil moisture is projected to decline by up to ~40%; increased evapotranspiration and reduced snowmelt, limiting soil water availability and groundwater recharge.	Western slopes of the Sierra Nevada; meadow systems and hydrologically connected landscapes	High
Ecological	Vegetation type conversion	High likelihood of transitions from forest to shrubland or grassland; ~30% of conifer forest areas in the Southern Sierra transitioned to non-forest cover during 2011–2020.	Southern Sierra Nevada; mixed-conifer and shrubland ecotones	High
Ecological	Increased wildfire severity and elevation shift	Burned areas are projected to increase by ~59% by 2040; expansion of high-severity fire into higher-elevation forests and earlier onset of the fire season.	Higher-elevation forests; Wildland–Urban Interface (WUI) zones across Sierra Nevada subregions	Very High
Ecological	Carbon storage vulnerability	Projections indicate net losses in aboveground forest carbon and tradeoffs between maximizing carbon storage and enhancing fire and drought resilience. Wet meadows store high densities of belowground carbon but are sensitive to hydrologic disruption.	Forested landscapes and wet meadows of the Sierra Nevada	High

Category	Vulnerability	Evidence (Observed & Projected)	Localized Context	Attribution Confidence
Social	Water supply reliability and flood risk	Earlier runoff peaks challenge reservoir operations balancing flood control and water storage; increased precipitation extremes and dry-to-wet whiplash events.	Sierra Nevada headwaters supplying the Central Valley; reservoir-dependent communities	High
Social	Public health impacts from wildfire smoke	Smoke exposure erodes more than 50% of previous PM2.5 air-quality improvements, affecting respiratory health and visibility.	Foothill and downwind communities across the Sierra Nevada region	High
Social	Climate vulnerability of rural and Tribal communities	More than one-third of the region lies in high or very high wildfire hazard zones. Low-income, elderly, disabled, and Tribal populations face disproportionate risks to safety, health, and recovery.	Rural towns, Tribal lands, and WUI communities	High
Economic	Hydropower and infrastructure seasonality	The shift from snowmelt-dominated summer inflows to increased winter runoff affects generation timing and reservoir management.	Sierra Nevada hydropower and conveyance systems	Medium
Economic	Recreation and resource-based livelihoods	Declining snowpack and intensifying wildfire seasons threaten winter recreation- and natural resource-dependent economies.	Recreation corridors and rural economies across Sierra Nevada subregions	High
Economic	Forest management and workforce strain	Rising suppression costs, fuel treatment demands, and post-fire recovery pressure small businesses and public agencies.	Forested landscapes and community workforce programs	Medium-High

3.1.4 Adaptation Actions

Table 3.1 provides a summary of key vulnerabilities in the Sierra Nevada, with localized context and confidence in attribution, across various systems (hydrological, ecological, social, and economic). The following sections describe adaptation actions for specific ecosystems, resources, or threats. However, an overarching approach that integrates the climate threats to Sierra Nevada ecosystems with their economic consequences to frontline communities is critical for identifying, prioritizing, and funding adaptation actions. The Eastern Sierra Sustainable Recreation Partnership: Sustainable Recreation and Tourism Initiative (SRTI), funded by the Sierra Nevada Conservancy through Proposition 68 funds, aims to develop a scalable and transferable model for such integration (MLTPA, 2022). Part of the SRTI approach was a baseline Natural Capital Assessment that was used to guide a Climate Adaptation and Resilience Assessment (TML, 2021), monetizing both the direct and indirect impacts of climate change on Eastern Sierra ecosystems to identify and prioritize a list of adaptation recommendations. This model provides an encouraging approach for integration that could be applied across sections of this report to help us better understand climate-driven impacts on communities in the Sierra Nevada.

Adaptive Management Decision Frameworks

There are at least six adaptive management decision frameworks utilized by United States federal, state, and local land managers that Carbon Storage and Biophysical Climate Feedbacks are designed to help decision-makers track progress and rigorously adjust management strategies dynamically when mitigating climate risks to local ecosystems. These frameworks include: Resistance, Resilience, Response (RRR) (Millar et al., 2007); Resistance, Resilience, Respond,

Realign, Reduce (5-R) (Millar et al., 2008); Resistance, Resilience, Transformation (Peterson St-Laurent et al., 2021); Resist, Accept, Direct (RAD) (Schuurman et al., 2020); Management Practice Assessment Tool (MPAT) (Abelson et al., 2022); and Monitor, Protect, Adapt, and Transform (Povak et al., 2024). To date, these decision frameworks have primarily been applied in ecosystem management or forestry contexts. However, a general framework that assesses which adaptive measures and interventions (e.g., resistance, response, transition, direction, etc.), based on time and location, are necessary to address unavoidable change while supporting long-term ecosystem health could be productively applied to other areas (e.g., water management, public health, etc.). While all frameworks are commonly used in an adaptive management context, certain frameworks may be better-suited based on local resources, community goals, and specific ecosystem type and conditions. For example, the 5-R framework is more appropriate to apply in situations where the system has been pushed far outside its natural range of variability (i.e., the system's current conditions differ significantly from their historical baseline) and effects are irreversible (see **Table A6**). In the sections below, we focus on a set of illustrative examples using the RRR framework.

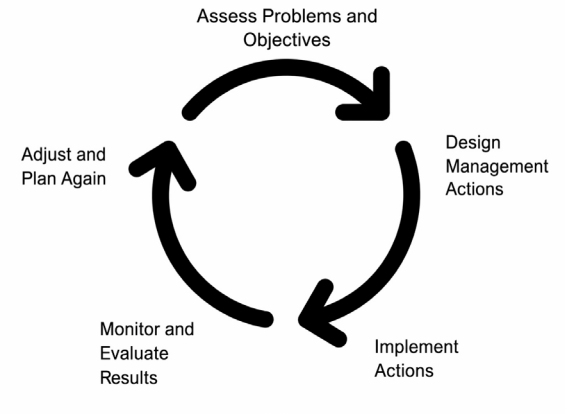


Figure 3.4: *Adaptive Management Decision Framework*

It is a core tenet of all adaptive management approaches to include research, monitoring, and evaluation as integral parts of the decision framework (**Figure 3.4**), ensuring that actions are informed by science, are responsive to change, and are continuously refined over time. For example, under the RRR framework: *resistance* actions are intended to prevent substantial disturbances and maintain unchanged forest character; *resilience* actions are designed to accommodate some degree of change but preserve forest cover and associated ecosystem functions, services, and economic benefits; and *response* actions intentionally accommodate change and focus on facilitating ecosystems to adaptively respond to changing conditions (Millar et al., 2007). Long-term monitoring through sentinel reference sites is critical for detecting trends, attributing change, and evaluating the effectiveness of resistance, resilience, and response actions under changing climate conditions (CSSN, n.d.). As a middle of the road option that balances climate change adaptation and maintaining some historical forest character, resilience-based management objectives are the most often recommended and implemented intervention in the Sierra Nevada forests at this time (e.g., Kershner, 2014; Peterson et al., 2011). In particular, with rapid climate change, resistance-based management techniques are increasingly ineffective, given the rate of warming and cascading impacts on drought events, wildfire risk, and insect and pathogen outbreaks.

FORESTS, OAK WOODLANDS, AND SHRUBLANDS

Table 3.2 lists example actions for each type of intervention, specific to forests in Sierra Nevada, using the RRR framework. In practice, multiple approaches within a particular intervention are often applied simultaneously in adaptive management scenarios. Sierra case studies (**Table 3.3**)

provide examples of implemented strategies, using the resilience intervention type, and their documented outcomes, demonstrating the effects of forest restoration on the ecosystem's overall resilience.

Table 3.2: *Intervention Types and Example Actions for Forests in the Sierra Nevada*

Intervention Type	Example Actions
Resistance	Continue fire suppression
Resistance	Use fuel reduction treatments
Resilience	Reduce forest densities to lower water stress, associated fire hazards, and risk of insect/pathogen outbreaks
Resilience	Reintroduce fire to the landscape through managed and prescribed fire
Resilience	Plant disease-resistant species/genotypes
Resilience	Expand planting palettes to regionally diverse species
Resilience	Increase forest connectivity for seed dispersal
Resilience	Increase landscape heterogeneity to improve ecological flexibility and reduce the spread of disturbance
Resilience	Maintain and expand seed orchards
Resilience	Managed grazing to increase recruitment but reduce fuels and exotic species
Response	Assisted migration or managed relocation of species to locations beyond native ranges where the future climate is projected to be favorable
Response	Plant genotypes drawn from areas already characterized to be analogous to the future climate
Response	Promote hardwood/broadleaf species in settings currently dominated by lower-elevation conifers
Response	Implement cessation planting or protect species where their sustainability is highly doubtful
Response	Increase ecosystem connectivity to facilitate migration in response to climate change
Response	Decommission roads and trails in locations where large and recurrent climate change-related impacts (e.g., flooding) are likely

Shrublands require very different interventions than forest ecosystems. For example, controlled burning and selective thinning predominantly opens up shrubland systems for invasion of non-native grasses, such as cheatgrass (D'Antonio et al., 2016), which not only decreases ecosystem resilience, but also increases future fire risk and accelerates type conversion. Effective adaptation actions for shrubland systems will require increased collaboration with Southern California regions that frequently interact with this vegetation type and with scientific researchers with expertise in shrubland ecology in an adaptive management framework. **Box 3.2** shares an example of a multi-partner collaboration that is crucial within the adaptive management framework for the giant sequoia.

Box 3.2: *Example of Collaborative Effort to Promote Giant Sequoia Fire Resilience*

The Giant Sequoia Lands Coalition (GSLC) is an organized collaboration of public and non-governmental organizations (NGOs) with a shared commitment to conserve giant sequoia grove ecosystems. The coalition is composed of all public agencies (federal, Tribal, state, local) and organizations that manage giant sequoia groves in public, Tribal or private nonprofit ownership. Affiliate partners include select federal and state conservation agencies, NGO conservation groups, and academic research partners dedicated to protecting giant sequoias and their ecosystems from emerging threats associated with climate change and the extended absence of natural, low-severity wildfire processes on the landscape.

Table 3.3: *Projects, Implemented Strategies, and Documented Outcomes of Forest Restoration on Resilience*

Project Name	Implemented Strategies Using the Resilience Intervention Type	Documented Outcomes
Sierra Foothills Research Extension Blue Oak Restoration Research and Demonstration Site	Planted 43 acres of previously cleared oak woodland with native blue oak seedlings	Identified restoration best practices by testing multiple propagation and seedling protection techniques
Sierra Foothills Research Extension Blue Oak Restoration Research and Demonstration Site	Planted 43 acres of previously cleared oak woodland with native blue oak seedlings	Planted over 6,500 seedlings with >60% survival
Sierra Foothills Research Extension Blue Oak Restoration Research and Demonstration Site	Planted 43 acres of previously cleared oak woodland with native blue oak seedlings	Created a platform for ongoing restoration research and demonstration activities
Giant Sequoia Land Trust Adaptive Management for Giant Sequoia Resilience to Climate Change	Thinned and piled ladder fuels and conducted prescribed and cultural burns led by Tribes	Reduced the unnatural accumulation of hazardous and combustible plant material on 10,335 acres since 2022, including 27 Sequoia groves in 2024 alone
Giant Sequoia Land Trust Adaptive Management for Giant Sequoia Resilience to Climate Change	Conducted scientific research and monitoring to better understand the long-term persistence of giant sequoias, tree hydrology, and the impact of wildfires and bark beetles on the health of giant sequoias.	Restoration work focused on areas that experienced uncharacteristically high wildfire intensity where overstory seed trees have died, burned seeds were not able to develop, and insufficient regeneration has occurred naturally
Increasing managed wildfire in the Illilouette Creek Basin (Yosemite National Park)	Allowed wildfires to burn when they did not threaten structures and extreme fire weather conditions were not anticipated in the near future	Has allowed wildfire to burn and only be suppressed under defined management conditions for over 40 years (Boisrame et al., 2017)
Increasing managed wildfire in the Illilouette Creek Basin (Yosemite National Park)	Allowed wildfires to burn when they did not threaten structures and extreme fire weather conditions were not anticipated in the near future	Has increased landscape heterogeneity and likely resilience to disturbance
Increasing managed wildfire in the Illilouette Creek Basin (Yosemite National Park)	Allowed wildfires to burn when they did not threaten structures and extreme fire weather conditions were not anticipated in the near future	Decreased forest areas by 22%, increased meadow areas by 200%, and increased shrub areas by 24%
Increasing managed wildfire in the Illilouette Creek Basin (Yosemite National Park)	Allowed wildfires to burn when they did not threaten structures and extreme fire weather conditions were not anticipated in the near future	Potentially increased or stabilized water yields (data collection ongoing)

RIPARIAN AND AQUATIC ECOSYSTEMS

Riparian and aquatic ecosystems have been stewarded by Indigenous Peoples for as long as they have existed. Indigenous land management practices such as cultural burning, selective harvesting, pruning, and riparian tending played a significant role in shaping vegetation structure, species composition, and ecosystem function prior to colonization (Gilio-Whitaker, 2019; Anderson, 2005; Anderson & Moratto, 1996). Large-scale erosion of ecological resilience in riparian and aquatic ecosystems began in the mid-1800s with the near complete extirpation of beavers from the region (Lanman et al., 2012). Similarly, the widespread and intense grazing of Sierra Nevada meadows by livestock is a very prominent driver in altering the ecological resilience of such ecosystems (Vernon et al., 2022; Myers et al., 2012). Management activities of Euro-American settlers that impacted stabilizing plant-soil-water feedbacks (e.g., heavy grazing), altered flows (e.g., road construction), disrupted habitat connectivity (e.g., large dam construction), or fundamentally changed biotic communities (e.g., non-native fish introduction) reduced the ability of these ecosystems to recover from disturbance and pushed many beyond the threshold of self-repair (Moyle et al., 2014; Menke, 1996). Resilience in riparian and aquatic ecosystems is driven by

hydrologic connectivity across ecosystems and landscapes that sustain high levels of biodiversity and complex interactions between *biotic* (i.e., living) and *abiotic* (i.e., non-living) elements (Akenbauer & Loheide, 2017; Viers & Rheinheimer, 2011; Yarnell et al., 2010; Loheide et al., 2009). In meadows, for example, shallow, meandering stream channels stabilized by dense root mats of wetland vegetation slow the flow of water through the ecosystem (Micheli & Krichner, 2002). This allows high flows to spread laterally over the floodplain, increasing the period of water retention on the landscape, attenuating flood events, and recharging groundwater reservoirs (Loheide et al., 2009; Hammersmark et al., 2008).

Table 3.4: *Intervention Types and Example Actions for Wet Meadows in the Sierra Nevada*

Type of Intervention	Example Actions
Resistance	Identify and conserve intact aquatic ecosystems and properly functioning meadows and fens – particularly those with high importance for biodiversity, habitat, hydrology, or carbon sequestration
Resistance	Manually remove encroaching conifers
Resilience	Reconnect floodplain hydrology in degraded meadows
Resilience	Address hydrologic alterations in the contributing watershed (e.g., flow concentrations, culverts, roads)
Resilience	Connect riparian and forest restoration efforts to improve watershed hydrology
Resilience	Conduct adaptive and experimental management of in-stream flows and habitats to enhance recovery of aquatic biodiversity
Resilience	Remove non-native fish and amphibians
Resilience	Expand planting palettes to include drought-tolerant and rhizomatous species
Resilience	Manage livestock grazing to prevent stream bank erosion and improve wildlife habitat
Resilience	Support the expansion of existing beaver populations and reintroduce beaver where they have been lost
Resilience	Build a network of local stewards to continue adaptive management
Resilience	Facilitate reconnection of Indigenous communities to lands they have traditionally stewarded
Resilience	Promote shared learning and creative solutions through applied science and collaborative networks
Response	Prioritize restoration in riparian and aquatic ecosystems with high biodiversity, less vulnerability to climate change, or higher likelihood of offering climate refugia
Response	Engineer restoration projects to plan for climate extremes
Response	Assisted migration or managed relocation of species to locations beyond native ranges where the future climate is projected to be favorable
Response	Translocate anadromous fish above dams for spawning
Response	Plant genotypes drawn from areas already characterized to be analogous to the future climate
Response	Allow for or facilitate the transition to alternative stable states (e.g., artificial elements within restored meadows, fish passage around dams, or inset floodplains within degraded meadows)
Response	Conduct scientific research to better understand the natural range of variability and guide transitions to maximize ecosystem function

Restoration efforts that seek to reconnect floodplain hydrology have been shown to increase vegetative growth (Reed et al., 2022), increase groundwater storage (Hammersmark et al., 2008; Tague et al., 2008), attenuate peak flow events (Ohara et al., 2014; Tague et al., 2008), improve habitat conditions (Campos et al., 2020; Herbst & Kane, 2009), and build soil organic matter (Morra et al., 2023; Reed et al., 2022). In aquatic ecosystems, activities that increase flow, improve habitat, and remove non-native fish and amphibians have been shown to increase biotic integrity and resilience (Kamoroff et al., 2020; Knapp et al., 2016; Herbst et al., 2012). In addition to

restoration actions, removing factors that exacerbate or drive ecosystem degradation (e.g., heavy grazing) could contribute to building adaptive resilience in riparian and aquatic ecosystems. The Resistance, Resilience, Response framework (described in *Forests, Oak Woodlands, and Shrublands* in *Section 3.1.4 Adaptation Actions*) can be used to guide adaptive actions under changing climate conditions.

Table 3.4 lists example actions for each intervention type, specific to wet meadows in Sierra Nevada, using the RRR framework. As mentioned earlier, multiple strategies within a particular intervention are often applied simultaneously.

As with forests and oak woodlands, resilience-based management practices are the most commonly applied interventions in Sierra Nevada meadows, though rapid climate change and high levels of degradation in these ecosystems may necessitate more responsive actions. To determine which actions will be the most effective for long-term meadow health, close collaboration and partnerships is key (**Box 3.3**).

Box 3.3: *Examples of Collaborative Efforts to Promote Climate Resilience in Sierra Nevada Meadows*

The Sierra Meadows Partnership is a consortium of over 90 entities engaged in meadow protection, management, restoration, and research. The Partnership was formed in 2016 to increase the pace, scale, inclusivity, and effectiveness of meadow restoration and conservation. The institutions and agencies involved—some of which have been pursuing these goals for decades—work to develop and share restoration best practices, improve permitting efficiency, study the impacts of disturbance and restoration on meadow ecology, and create climate-smart tools to inform adaptive management actions. The Partnership is well on its way to achieving its goal of protecting or restoring 30,000 acres of meadows in the Sierra Nevada by 2030.

Mountain meadows are places of great importance for Indigenous groups throughout the Sierra Nevada and have been stewarded by Indigenous Peoples for centuries for food, medicines, wildlife, and cultural purposes. Collaborative efforts to restore Indigenous ownership and stewardship are examples of strategies to increase social-ecological resilience in meadows. In 2019, the Maidu Summit Consortium collaborated with the Feather River Land Trust and the California Department of Fish and Wildlife to re-acquire 2,325 acres of one of the most ecologically and culturally significant meadows in the Northern Sierra. The Maidu Summit Consortium is now working with the Sierra Meadows Partnership to share cultural practices, restore the meadow, and develop a Tribal meadow restoration workforce.

WILDLIFE

For wildlife species that will be adversely affected by climate change, certain human interventions may offset negative effects by increasing resilience of wildlife populations. Helping wildlife adapt to climate change will generally require us to maintain their habitat conditions, both in size and long-term health, to support viable populations. Given the large effect fire is currently having on wildlife habitat in the Sierra Nevada landscape, our ability to curb the increasing frequency and severity of fires in the near term, with a goal of a mixed severity fire regime that promotes heterogeneity successional states, will have large implications for the future of Sierra Nevada wildlife. As with habitat-specific adaptation actions, resilience-based management strategies are most often implemented for wildlife, though rapid climate change, declining populations of wildlife, and a growing climate adaptation gap may necessitate more innovative actions (Stein et al., 2024). Using the RRR framework, **Table 3.5** lists example actions for each intervention type for wildlife conservation.

Table 3.5: *Intervention Types and Example Actions for Wildlife Conservation in the Sierra Nevada*

Type of Intervention	Example Actions
Resistance	Identify and protect important populations of rare species and subspecies
Resilience	Promote forest resilience to future fires
Resilience	Embrace an active mixed severity fire regime to promote seral-stage heterogeneity in forested landscapes
Resilience	Restore degraded keystone ecosystems that offer disproportionate benefits for wildlife relative to their land area (e.g., wet meadows, riparian areas, aspen)
Resilience	Promote connectivity of wildlife migration corridors
Resilience	Monitor for and remove invasive species
Resilience	Enhance monitoring programs for wildlife and ecosystems
Response	Translocate individuals or populations of species into favorable habitats
Response	Establish captive populations of species or subspecies facing extinction

WILDFIRE

Wildfires in the Sierra Nevada are generating widespread ecological impacts that are reshaping the region's forests and biodiversity. These conditions have contributed to catastrophic tree mortality, most notably among giant sequoias, a species once thought to be nearly fire-immune (Keeley & Pausas, 2025). The 2020 Castle Fire, the 2021 Kings Canyon and Sequoia National Parks (KNP) Complex Fire, and the Windy Fire, which occurred in this region, could collectively result in the loss of a large share of the world's mature sequoias, as indicated by previous studies of fires in other regions (Shive et al., 2022). The ecological consequences extend beyond iconic species—repeated large fires are eroding the regenerative capacity of conifer forests, creating expansive patches where natural recovery is limited, and accelerating transitions toward shrubland and grassland ecosystems with reduced carbon storage and cultural value (Jasperse et al., 2025; Zhang et al., 2025; Zhou et al., 2025). Wildlife habitats have also been diminished, including those critical for the Pacific fisher and California spotted owl, further compounding the stress on species already facing climate-related pressures (Hart et al., 2025). These transformations threaten the long-term integrity of Sierra Nevada forests and the ecosystem services they provide.

The hydrological and societal consequences of wildfire are equally profound. Burned landscapes exhibit destabilized soils, leading to elevated erosion, debris flows, and sediment loading that impair reservoirs and downstream water infrastructure (McNeece, 2025). Post-fire reductions in canopy cover can significantly suppress evapotranspiration for more than a decade, altering watershed water balances and shifting the timing of streamflow (Collar et al., 2023). These hydrologic changes amplify risks to water quality, with post-fire runoff elevating turbidity, heavy metals, and nutrient loads that strain drinking water systems and increase treatment costs (Paul et al., 2022). Air quality impacts are equally severe. In the western United States, increased exposure to fine particulate matter (PM2.5) from wildfires is now linked to anthropogenic climate change, erasing decades of progress in California to reduce PM2.5 (Law et al., 2025; Connolly et al., 2024). Tribal people and other communities at the wildland-urban interface face the greatest exposure, with heightened risks of respiratory illness, economic instability, and displacement. Insurance losses reflect this growing vulnerability, with more than 350,000 home insurance policies at risk due to the threat of wildfire, which could affect residents of Sierra Nevada counties

(Hanes, 2025; Serleth, 2024). Together, these impacts underscore that wildfire is not only an ecological disturbance but is also a systemic challenge to forests, water security, public health, and community resilience in the Sierra Nevada.

3.2 Water Resources

KEY MESSAGE:

Climate change is fundamentally transforming Sierra Nevada's role as California's primary water source by undermining the natural snowpack reservoir that sustains the state. Rising temperatures are causing precipitation to fall increasingly as rain instead of snow, leading to a dramatic decline in snowpack, earlier and faster snowmelt, and a shift in peak streamflow from late-spring to mid-winter. This hydrologic transformation creates a dangerous seasonal mismatch between supply and demand, elevating the risk of winter floods while drastically reducing water availability during the dry summer months when agricultural, municipal, and ecological demand is greatest. These changes are further compounded by more frequent and severe wildfires, which degrade water quality and increase erosion, as well as by more intense droughts that strain both surface and groundwater systems. Adapting to this new reality requires an urgent, integrated approach that modernizes water infrastructure, expands managed aquifer recharge, restores natural ecosystems like forests and meadows to enhance water retention, and improves forecasting to manage the increasingly volatile swings between flood and drought.

3.2.1 Introduction

Climate change continues to pose significant challenges to water resources in the Sierra Nevada, with direct consequences for local communities and millions of downstream users in the Central Valley and beyond. The Sierra Nevada snowpack, the main source of California's water during spring and summer (SNC, n.d.), is now increasingly threatened by rising temperatures, altering snowpack levels, snowmelt timing, and streamflow dynamics (Chapter 2 & **Table 3.1**). These shifts are expected to significantly affect water availability for urban areas, agriculture, and ecosystems across the state. For instance, the Sacramento–San Joaquin Delta irrigates 3.7 million acres of farmland and supplies all or part of the water for over 27 million Californians in urban centers that are reliant on exported water (DSC, 2021).

Spring snowmelt supports both human and natural systems, providing essential water from the Sierra Nevada westward to California's coastline and eastward to the deserts of eastern California and western Nevada. At higher elevations, snowmelt remains a primary water source for local communities and montane ecosystems. The interconnected nature of upstream headwaters and downstream water uses underscores the importance of sustainable water management. The state's extensive water infrastructure, including dams, aqueducts, and levees, plays a vital role in regulating seasonal variability. Many structures serve multiple functions: dams store water for dry season use, maintain environmental flows, control floods, and generate hydropower; levees and waterway networks protect against flooding while maintaining habitat for endangered species (CDWR, 2024).

Despite being sparsely populated compared to urban regions, Sierra Nevada communities rely heavily on surface water for residential, commercial, and agricultural purposes, as well as for

recreational activities like fishing, boating, rafting, and skiing. Changes to snowpack, temperature, and precipitation can thereby significantly impact the socioeconomic structure of these communities. Water resources are integral to the region's tourism-driven economy, though these uses receive less attention than urban and agricultural demands downstream. Given that most Sierra Nevada populations are rural and economically disadvantaged, they face distinct challenges in managing water resources due to limited financial and human capacity. Small public and private water systems, often staffed part-time or operated by community volunteers, struggle to maintain infrastructure and fund improvements. Regulatory barriers, such as Proposition 218 (PPIC, 2025) which requires voter approval or formal protest procedures for certain rate increases and limits fees to the cost of service, further hinder the ability of some communities to raise funds for necessary upgrades and maintenance.

Warmer winter storms are increasingly producing rain-on-snow events that heighten winter flood risks and complicate reservoir operations (Soderquist, 2021; White et al., 2019). Earlier runoff and reduced snowpack are also expected to limit groundwater recharge and increase pressure on aquifers (Siirila-Woodburn et al., 2021). At the same time, large wildfires are altering watershed processes by changing evapotranspiration patterns, increasing sediment loads, and degrading water quality (Busari et al., 2025; Dahm et al., 2025). California's reservoirs could lose up to 15% of their capacity to sedimentation (Minear & Kondolf, 2009), which may further intensify with increasing wildfires. Together, these changes are reshaping the hydrologic foundation of the state and creating new vulnerabilities for both downstream users and Sierra Nevada communities.

3.2.2 Climate Effects, Trends, and Projections

CLIMATE EFFECTS

The trends of rising temperature and shifting precipitation patterns, coupled with increasing extreme weather events, are already straining California's water management strategies (Corringham et al., 2019; Mote et al., 2018; Regonda et al., 2005). While projected changes in the long-term precipitation trends in Sierra Nevada are small compared the interannual variability and are not consistent compared to expected temperature changes (Chapter 2), the extreme precipitation events—such as intense atmospheric rivers, rain-on-snow events, and prolonged droughts—are expected to intensify (Huang et al., 2020; Gershunov et al., 2019; Musselman et al., 2018; Swain et al., 2018; Williams et al., 2015). However, the frequency and severity of such events can be highly variable. For example, the frequency of rain-on-snow events is expected to increase at higher elevations with the opposite expected to occur at lower elevations due to low to no snowpack (Musselman et al., 2018).

Given the complex geography of the Sierra Nevada, changes in precipitation and hydrology will vary across the region, necessitating sustainable adaptation and policy strategies for resource and ecosystem management and climate change resiliency. In addition, water managers will need to prepare for more frequent, rapid swings between wet and dry conditions (Swain et al., 2018). Such transitions will also stress aging infrastructure (e.g., flood control and conveyance systems), posing additional challenges for water management practices.

Increased evapotranspiration, driven by higher vapor pressure deficit and longer growing seasons, the expansion of vegetation into cooler areas, and higher water demands from soils and plants,

will put additional pressure on water resources (Rungee et al., 2021; Goulden & Bales, 2014; Goulden et al., 2012). A recent study shows that higher evaporative demand is the main cause of drought under climate change rather than the decrease in precipitation (Zhuang et al., 2024). Drier conditions can also provide more fuel for potential wildfires. While elevated atmospheric CO_2 levels may improve plant water-use efficiency (Guo et al., 2022), this benefit could be counteracted by nutrient limitations (Chai et al., 2024), or expansion of vegetation to cooler areas at high-elevations where temperature currently limits the increased growth of plants, leading to higher overall water consumption (Goulden & Bales, 2014). Recent modeling and observational studies further suggest that sustained warming and an elevated vapor pressure deficit can suppress growth and increase mortality risk for plants, thereby opposing CO_2 fertilization effects in water-limited mountain ecosystems (Sperry et al., 2019). This implies that the elevation range and frequency of wildfires may continue to shift upward and increase in the future, consistent with historical trends and projections (Alizadeh et al., 2021; Li & Banerjee, 2021; AghaKouchak et al., 2018). As extreme events become more prevalent and severe, their sequencing can also enhance local and remote effects on natural resources and communities. Furthermore, climate events, whether extreme or not, can have compounding effects that amplify the impacts of individual hazards (Zscheischler et al., 2020; AghaKouchak et al., 2018).

Recent observations highlight that these changes are occurring alongside a pronounced warming trend, with mean warm day temperatures in the Sierra Nevada increasing by approximately 2.9°F (1.6°C) since the early 1970s (Williams et al., 2019). Winter and spring warming is raising the elevation at which snow accumulates, reducing overall snowpack volume and shifting the timing of runoff (McDermott, 2025; Hatchett et al., 2017). Because the snowpack functions as a natural reservoir, these shifts have direct consequences for urban, agricultural, and ecological water demands. Precipitation is also becoming more variable and intense, with evidence of pronounced *whiplash* between extreme wet and dry years (Swain et al., 2018). Atmospheric rivers are contributing to a growing share of annual precipitation, with individual storms becoming more frequent and intense during winter (Dettinger et al., 2020; Gershunov et al., 2019). These storms deliver large volumes of rainfall over short periods, particularly at lower elevations where snowlines have moved upward, leading to earlier- and higher-magnitude runoff peaks that elevate flood risks and complicate reservoir operations. Prolonged dry spells between these intense storms are becoming more common, amplifying drought severity and placing additional stress on both surface and groundwater systems (Meyers et al., 2021). Warmer conditions further accelerate snowpack and soil moisture depletion during droughts, causing earlier streamflow recession and reduced groundwater recharge (Diffenbaugh et al., 2015). These climatic shifts are also transforming wildfire regimes. Earlier snowmelt, longer dry seasons, and hotter summers are creating conditions that favor larger and more severe fires (Abatzoglou et al., 2017). Wildfires also trigger cascading hydrologic impacts, including reduced canopy cover, suppressed evapotranspiration, flashier runoff, and increased sediment and nutrient loads, all of which degrade water quality and strain infrastructure. The combined influence of warming, shifting precipitation, intensifying extremes, vegetation changes, and wildfire disturbances is fundamentally transforming the Sierra Nevada's climate-hydrology-ecosystem interactions, undermining snowpack reliability, increasing flood hazards, reducing groundwater recharge opportunities, and elevating risks to water availability, infrastructure, and public safety.

SNOWPACK

Seasonal snowpack in the Sierra Nevada serves as a dominant source of managed runoff, delivering a major fraction of spring and summer inflows to California's reservoir and conveyance systems (see *Section 2.3 Snowpack Trends* for regional snowpack trends). However, it is anticipated that future snowmelt contributions to runoff in the Sierra Nevada will decline from 73% to 38% by the year 2100 under RCP 8.5 (Li et al., 2017).

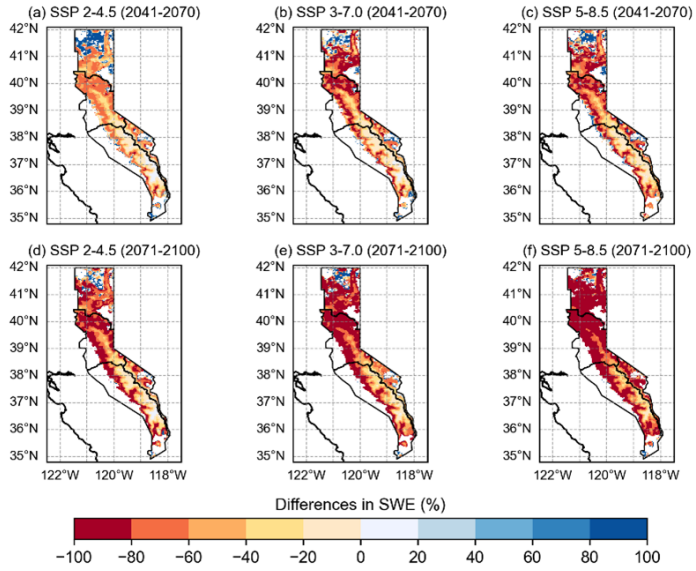


Figure 3.5: *Projected percentage changes in April 1 snow-water equivalent, relative to historical mean (1981–2010), for 2041–2070 (a, b, c) and 2071–2100 (d, e, f), under SSP 2–4.5 (a, d), SSP 3–7.0 (b, e) and SSP 5–8.5 (c, f). We estimate approximately 90% SWE loss in 30, 38, and 60% of the currently snow-covered Sierra Nevada by the end-century under SSP 2–4.5, SSP 3–7.0, and SSP 5–8.5, respectively. The corresponding areal losses by mid-century are 16, 21, and 19%, under SSP 2–4.5, SSP 3–7.0, and SSP 5–8.5, respectively.*

Future projections indicate continued and accelerated declines in snowpack across all climate projections (*Section 2.3 Snowpack Trends*; **Figure 3.5**). While snowpack is expected to keep declining over the long term, it won't be a steady drop (**Figures A1–A3**). Instead, we may see years with exceptional snow in between (e.g., year 2023). In the Northeastern Sierra, snow is likely to disappear completely by mid-century under SSP 5–8.5, and in the Southeastern Sierra, snowfall may only happen at infrequent intervals (**Figures A1–A3**). Since the eastern slopes of the Sierra Nevada contain a larger proportion of high-elevation watersheds, this may potentially provide some buffering against snowpack loss; however, substantial changes in snow accumulation and runoff timing are still expected (Ficklin et al., 2012). In the Northwestern Sierra Nevada, percentage increases of snowfall appear large, but these reflect small absolute changes amplified by a very low baseline (**Figure A4**).

Projected shifts in earlier maximum reservoir storage in California will need to be balanced with flood and drought risks (Wrzesien et al., 2022). With expected shifts in the timing and distribution of snowmelt, changes in the streamflow and recharge necessitate adaptation strategies in sectors such as water and energy management and distribution.

Adapting to these changing snowpack and runoff dynamics will require a mix of infrastructure modernization, operational flexibility, and nature-based strategies. Reservoir operations will need to be re-optimized to capture earlier runoff while maintaining adequate flood protection, supported by improved forecasting and real-time monitoring (Corringham et al., 2019; Mote et al., 2018). Managed aquifer recharge (MAR) and conjunctive use strategies offer opportunities to store excess winter flows underground for use during the dry season (Sahuquillo, 2017). Forest

and meadow restoration can enhance local snow retention and delay melt, providing additional buffering against earlier runoff (Pastore et al., 2025; Hunt et al., 2018). Long-term planning will also need to address increasingly rain-dominated winters, shorter snow seasons, and shifting runoff patterns by upgrading conveyance and storage infrastructure and revising flood control rules. Effective adaptation will require coordinated action across water, energy, and ecosystem management sectors to balance shifting flood and drought risks while sustaining the multiple functions historically supported by the Sierra Nevada snowpack.

FLOODS

An increase in winter runoff (*Section 2.4 Trends in Regional Drying and Runoff*) suggests a heightened risk of more frequent and severe flooding, posing significant challenges for water infrastructure and downstream communities (Halofsky et al., 2021). The Sierra Nevada is the primary source of California's major flood events, driven by increased winter rainfall, rain-on-snow occurrences, and winter-season snowmelt (Das et al., 2011; Huang & Swain, 2022). Both Northern and Southern subregions of the Sierra Nevada are susceptible to flood risks. By the end of the century, 50-year return period flood discharges are projected to rise by 30–90% in the Northern Sierra and by 50–100% in the Southern Sierra, depending on the climate model used (Das et al., 2013). These projected increases in flood magnitude exceed natural variability at the 95% confidence level, with statistically significant changes emerging as early as 2035 under the SRES A2 scenario (a high-emissions scenario used in the Coupled Model Intercomparison Project Phase 3, comparable to SSP 3–7.0). By the late 21st century, the Northern Sierra Nevada is projected to see notable declines in rain-on-snow areas, likely due to reduced snow accumulation at its lower elevations (Das et al., 2011; Stewart et al., 2015). In contrast, the Southern Sierra shows less change, possibly due to offsetting effects—less snow at lower elevations reduces rain-on-snow potential while warming increases rainfall at higher elevations. These opposing influences may be more pronounced in the Southern Sierra due to its greater elevation range.

The risk of flooding will increase further due to the projected increase in intensity of atmospheric rivers and more part of precipitation falling as rain compared to snow (Huang & Swain, 2022). Many rural Sierra Nevada communities lack the infrastructure to cope with heightened winter flood risks, while downstream reservoirs and conveyance systems may also face increased strain.

Warmer winters are expected to raise snowlines and increase both the frequency and intensity of rain-on-snow events, leading to larger and earlier runoff peaks (Huang et al., 2018; Musselman et al., 2018). Intensifying atmospheric river storms are delivering greater volumes of rainfall over shorter periods, further elevating winter flood risks for foothill communities and downstream valleys (Dettinger et al., 2020; Gershunov et al., 2019). Adapting to these changing flood-regimes will require a combination of infrastructure modernization, operational flexibility, nature-based solutions, and most importantly, smart and adaptive water policies. Much of California's existing flood control infrastructure was designed for a snow-dominated hydrologic regime; with earlier runoff and larger winter flows, reservoir rule curves will need to be updated to capture earlier inflows without compromising flood protection (Wrzesien et al., 2022). Enhanced forecasting, real-time monitoring, and improved seasonal prediction can support more dynamic reservoir operations (Delaney et al., 2020; Guo et al., 2021). Nature-based approaches such as floodplain reconnection, levee setbacks, and watershed restoration can help retain more water upstream,

attenuate flood peaks, and provide ecological co-benefits (Chambers, 2025). Coordinated planning across agencies will be essential to address the combined risks of extreme precipitation, rain-on-snow events, and aging infrastructure, ultimately improving the resilience of Sierra Nevada communities and California's broader water management ecosystem to future flood extremes.

SURFACE WATER

Elevation-dependent changes in snow and precipitation patterns also influence hydrology, controlling the sources of streamflow and groundwater as shown by isotopic analyses in snowmelt-fed catchments (Liu et al., 2024). These changes modify seasonal water storage and runoff timing, altering soil moisture distribution across elevations and highlighting the vulnerability of mid- and high-elevation water sources to warming.

The future availability of annual surface water remains unclear as projected changes in runoff timing and decline in summer streamflow (*Section 2.4 Trends in Regional Drying and Runoff*) will pose challenges for certain water management operations and infrastructure. Earlier snowmelt is already altering streamflow patterns across the western United States, with peak runoff into snow-fed rivers, such as the Sacramento River, shifting to earlier in the year by up to a month (Milanes et al., 2022; Fritze et al., 2011).

Projected declines in spring and summer streamflow will not affect all sub-watersheds equally (Ficklin et al., 2012; Null et al., 2010). Mid-elevation watersheds are expected to experience the greatest reductions, driven by significant losses in snow accumulation. In contrast, higher-elevation basins may be more resilient due to persistently cooler temperatures. Regional analyses indicate that watersheds in the Northern Sierra Nevada are particularly vulnerable to reductions in annual flow, while those in the south-central Sierra are more likely to face altered runoff timing and prolonged low-flow periods (Null et al., 2010). However, volcanic terrains in the northern Sierra Nevada with strong groundwater connectivity may partially buffer snowmelt-driven flow reductions by sustaining late-season baseflow, consistent with evidence that groundwater-dominated basins exhibit slower recession (Safeeq et al., 2014). However, groundwater-dominated basins have more to lose under a warmer climate as the vegetation will likely draw more water from deeper storage to fulfill evaporative demand. While most modeling studies agree that there will be a reduction in streamflow during summer, the exact amount of reduction depends on climate and hydrological models used and remains uncertain (Miller et al., 2021).

These hydrologic shifts complicate water management, necessitate adjustments in water storage and flood management strategies, and a watershed-specific approach to adaptation (Milanes et al., 2022). With uncertainties remaining in total streamflow projections, targeted regional assessments are critical for effective planning and resilience-building (Das et al., 2011).

By the end of the century, dry season baseflows are projected to decline substantially across Sierra-fed rivers, increasing stress on water supply systems (Ayers et al., 2024). These hydrologic shifts, including earlier runoff peaks, lower summer baseflows, and greater variability, are expected to place added strain on aging surface water infrastructure that was originally designed for a snowmelt-dominated regime (Wrzesien et al., 2022; Mote et al., 2018). Adapting Sierra Nevada's surface water systems to these changes will require a combination of infrastructure modernization, operational flexibility, and watershed-specific strategies. Forecast-informed

reservoir operations can help capture earlier runoff while maintaining flood protection, supported by improved seasonal prediction and real-time monitoring. Expanding groundwater recharge and conjunctive use strategies can store excess winter flows for use during dry periods, while conveyance systems and spillways will need to be updated to accommodate larger and earlier inflows. Reoperating reservoirs will be essential to balance water supply, hydropower generation, and environmental flow objectives. Ecosystem-based measures, such as meadow and forest restoration, can enhance infiltration, extend baseflows, and buffer hydrologic extremes at the source. Given spatial variability in hydrologic responses, watershed-based adaptation strategies are expected to be more effective, particularly in mid-elevation and Northern Sierra basins that face the most severe summer flow reductions. Coordinated planning between upstream and downstream agencies will be critical to ensure that water allocations, flood management, and ecosystem protection remain effective under shifting hydrologic regimes.

UNCERTAINTIES

Rapid declines in Sierra Nevada snowpack and shifts toward earlier spring runoff are very likely, although uncertainties remain regarding how well downscaled models capture local elevational gradients, with some models overestimating stored snow water (Rahimi et al., 2024). Improved quantification of snow-to-rain transitions, rain-on-snow events, and snow droughts is needed to better understand how these processes affect runoff timing and peak flows. In many headwater and montane catchments, groundwater systems, springs, meadow water tables, and fractured-rock aquifers remain poorly monitored and understood. Mountain recharge is closely tied to snowmelt infiltration, so reductions in snowpack can strongly limit recharge processes (Urióstegui et al., 2017), and climate-driven declines in montane recharge may worsen groundwater stress (Levy et al., 2020). Expanded in-situ monitoring (i.e., collecting data directly at the source) using wells, groundwater level sensors, and tracers to estimate transit times is required to capture responses at appropriate spatial and temporal scales. In addition, significant questions remain regarding the fluvial and ecosystem impacts of flood-based managed aquifer recharge (or Flood-MAR), including how episodic high-flow infiltration alters channel morphology, hyporheic exchange, sediment transport, riparian vegetation recruitment, and biogeochemical cycling. The extent to which Flood-MAR modifies thermal regimes, nutrient dynamics, and habitat suitability for aquatic and riparian species, as well as its cumulative effects on downstream flow timing and water quality, remains poorly constrained and warrants integrated field experiments and coupled surface-subsurface modeling.

Water quality is also vulnerable, as lower baseflows, higher water temperatures, and storm-driven runoff from wildfire-affected slopes increase risks of sediment intrusion, nutrient loading, and contaminant pulses. Better sampling of dissolved oxygen, turbidity, nutrients, and trace contaminants, especially following extreme events, is needed to anticipate impacts on ecosystems and drinking water treatment as observational networks are too coarse to detect these dynamics at high frequency. Beyond physico-chemical metrics, knowledge of aquatic biodiversity across Sierra Nevada streams, wetlands, and headwater systems remains limited due to historically sparse and spatially uneven biological monitoring. Although recent efforts, including the All Taxa Biodiversity Inventory (ATBI) program (Nichols & Langdon, 2007), have begun to improve taxonomic coverage and baseline data for aquatic and riparian biota, gaps persist in linking species distributions, population dynamics, and functional traits to flow regimes, thermal stress,

water quality, and disturbance gradients (e.g., wildfire and flood events). Expanding coordinated, long-term biological surveys alongside hydrologic and water quality monitoring is needed to assess ecosystem vulnerability, resilience, and adaptive capacity under ongoing climate change.

Climate extremes, such as atmospheric rivers, drought, and heat waves, are projected to intensify, yet significant uncertainty remains regarding their intensity, frequency, and cascading impacts. Intensifying atmospheric rivers and rain-on-snow events are expected to increase flood risks, yet many Sierra watersheds lack robust modeling of future flood frequencies, durations, and timing under climate change. The interactions between post-fire burn scars, debris flows, and flood hydrology remain poorly constrained, calling for enhanced forecasting frameworks and empirical calibration in fire-affected basins to support resilient infrastructure planning. Small, remote communities across the Sierra Nevada are especially vulnerable to shifting water reliability due to limited infrastructure, underscoring the importance of collaborating with Tribes and integrating social vulnerability, and adaptive capacity into water planning so that adaptation strategies (e.g., small-scale storage, demand management, and conjunctive use) are feasible and equitable. Finally, the region lacks a fully integrated hydro-climatic observation and modeling network. Expanding snowpack sensors, streamflow gauges, groundwater level and quality monitoring, and real-time data assimilation would strengthen hydrologic forecasting, scenario planning, and adaptive water management under uncertainty. Accurate projections of extremes and thresholds (e.g., rain-on-snow flood risks, prolonged heat stress, atmospheric vapor transport) are critical for actionable decision-making and for protecting vulnerable populations and ecosystems.

3.2.3 Vulnerability

The combined effects of reduced snowpack and increased evapotranspiration are projected to significantly alter the region's hydrology, including changes in soil moisture, runoff patterns, and groundwater recharge, with cascading impacts on wildfire risk, ecological integrity and biodiversity, human communities, and water resources statewide. Beyond these individual effects, the region is expected to face compound and cascading hazards. Rainfall intensification is projected to occur more than six times per year under RCP 8.5, where the 15-minute rainfall intensity exceeds the threshold for post-fire debris flows, compared to only 1.5 exceedances per year historically (Thomas et al., 2024). Concurrently, multi-day heat waves occurring during drought periods are projected to increase in both frequency and intensity during the mid- and late-21st century (Mazdiyasni & AghaKouchak, 2015; Diffenbaugh et al., 2015). These overlapping extremes may act synergistically, exacerbating impacts on soil moisture, streamflow, reservoir operations, and energy infrastructure (Chiang et al., 2018). Together, these processes illustrate how climate-driven changes can produce cascading effects, where one extreme event, such as wildfire, heightens vulnerability to subsequent hazards
(e.g., flash floods and debris flows) (Reid et al., 2016).

SURFACE WATER SUPPLIES

The Sierra Nevada continues to serve as California's natural water tower, storing winter precipitation as snow and releasing it gradually during spring and summer. A warming climate has already altered this balance, and vulnerabilities identified in earlier assessments have become more pronounced over the past decade. Observations and modeling studies show that peak

streamflow is now occurring several weeks earlier than in the mid-20th century, with many lower elevation basins shifting peak discharge from April–May to March (Siirila-Woodburn et al., 2021; Stewart et al., 2005). Earlier runoff increases winter and early spring flows, heightening flood risks, while reducing late-summer flows when agricultural, municipal, and ecological demands are greatest. This seasonal mismatch between supply and demand is one of the central vulnerabilities for California's water management.

Snowpack decline is emerging as one of the clearest signals of climate change in the Sierra Nevada region. April 1 SWE, historically a strong indicator of water availability (Wilson et al., 2024), has already diminished across the northern and central Sierra. The reduction in snowpack storage undermines the natural buffering capacity of the range, leaving reservoirs and groundwater systems to absorb greater strain during dry summers and drought years. Earlier melt-out will also increase drought stress to our forested ecosystem and exacerbate tree mortality (Casirati et al., 2023). Trees will increasingly rely on deeper water storage, leading to runoff prediction uncertainty and an overall reduction in runoff ratio (Lapides et al., 2022).

Reservoir operations illustrate another dimension of vulnerability. Model simulations that couple hydrology with operations show that carryover storage in major Northern Sierra reservoirs is projected to decline by late century, even under moderate emissions (Knowles et al., 2018). Although reservoirs in the Southern Sierra Nevada could show somewhat greater resilience due to higher elevation snowpacks, they could be vulnerable to shortages during prolonged droughts. Smaller local reservoirs, with limited operational flexibility, are even more exposed to variability in runoff timing.

Compounding hazards further exacerbate these risks. Rising temperatures not only accelerate snowmelt but also intensify open-water evaporation from reservoirs and rivers (Wang et al., 2024). Consecutive dry years have demonstrated how reservoirs fail to recover between events, reducing carryover storage and forcing curtailments to both urban and agricultural users (Swain et al., 2018; Diffenbaugh et al., 2015). In addition, compound drought and heat wave events suppress runoff efficiency and increase evaporative demand, further constraining surface-water supplies (Zhao et al., 2024). These dynamics could cascade into ecological vulnerabilities, reducing cold-water habitat for fish and intensifying wildfire risks by coinciding with the driest fuel conditions.

In addition to climate-driven changes in snowpack, runoff timing, and streamflow magnitude, surface water supplies in the Sierra Nevada are increasingly shaped by demand-side vulnerabilities. High per capita and sectoral water use, aging conveyance and distribution infrastructure, and limited adoption of conservation-oriented technologies and pricing structures can amplify exposure to hydrologic variability and drought. These human and institutional dimensions of vulnerability determine how effectively declining or more variable supplies translate into actual water scarcity for both in-region communities and downstream users who rely on Sierra Nevada water resources. Water conservation therefore represents a critical adaptive pathway for reducing surface water vulnerability under future climate conditions. Demand-side strategies across residential, agricultural, and tourism sectors, including high-efficiency fixtures and appliances, precision irrigation and managed landscape transitions, system modernization and leak reduction, and regulatory or incentive-based pricing frameworks, can substantially lower water demand while maintaining essential services. By reducing pressure on surface water withdrawals and associated energy use for conveyance and treatment, conservation measures

can enhance the resilience of coupled water-energy systems and improve the reliability of existing and declining surface water supplies.

Overall, the vulnerabilities of Sierra Nevada surface-water supplies are deepening as the century progresses. Earlier runoff, declining snowpack, operational challenges in reservoirs, and the increasing frequency of compounding extremes collectively threaten the reliability of water deliveries, the resilience of ecosystems, and the well-being of local communities (Chakraborty et al., 2023; Duan et al., 2019). Effective management could include smart water policies built around adaptive reservoir operations, promoting Flood-MAR, the integration of groundwater and surface-water strategies, diversification of water portfolios, and expanded forecasting systems to anticipate rapid shifts in water availability. Without such interventions, the Sierra Nevada's capacity to serve as California's natural reservoir will become increasingly compromised under a changing climate.

GROUNDWATER

Groundwater in the Sierra Nevada itself is an essential but often overlooked component of the region's hydrology. Mountain aquifers provide baseflow to rivers, sustain high-elevation ecosystems, and connect through mountain block and mountain front recharge to the deeper aquifers of the Central Valley. Recent isotopic and geochemical studies suggest that as much as 31–53% of Central Valley recharge originates in the Sierra Nevada through these mountain system pathways (Werth et al., 2025; Armengol et al., 2024). This dependence makes Sierra Nevada recharge processes central to both local and statewide groundwater sustainability.

Climate change directly threatens these recharge pathways. Warming is reducing snowpack storage and shifting runoff earlier in the year (Siirila-Woodburn et al., 2021; Mote et al., 2018). Earlier streamflow peaks translate to less infiltration during the traditional late spring recharge window, particularly in basins where groundwater replenishment depends on slower and sustained snowmelt inputs. High-resolution CMIP6 simulations show that recharge becomes increasingly concentrated in winter months by mid-century, while late-century conditions produce fewer recharge events and greater evaporative losses (Rhoades et al., 2022). Regional differences emerge: Northern Sierra watersheds, with lower snow elevations, are most sensitive to rain-snow transitions, while Southern Sierra basins retain more snow but still face compressed melt seasons that limit percolation opportunities (Klos et al., 2014).

Observations confirm the stressors projected by these models. Gravity Recovery and Climate Experiment (GRACE) satellite records show that groundwater in Sierra-fed basins declined sharply during the 2012–2016 and 2020–2022 droughts, with recovery lagging even in wet years (Lapides et al., 2022; Liu et al., 2022). The extreme precipitation of 2022–2023 demonstrated the potential to replenish storage— MAR across California stored more than 4 million acre-feet that year (CDWR, 2024), yet much of the Sierra's rapid winter runoff bypassed infiltration because conveyance and spreading infrastructure were insufficient to capture peak flows.

The policy landscape is also evolving. The Sustainable Groundwater Management Act (SGMA) requires local basins to reach sustainability by 2042 (CWIN, 2025), and Groundwater Sustainability Plans (GSPs) are now expected to incorporate climate change in their recharge estimates and sustainable yield calculations. However, external reviews find that many plans still underestimate climate impacts and lack robust accounting of mountain system recharge (Arthur et al., 2022).

The most pressing vulnerabilities for Sierra Nevada groundwater are thus threefold. First, timing shifts in runoff compress recharge into earlier, less efficient windows. Second, climate extremes such as back-to-back drought years suppress infiltration opportunities and increase demand on limited storage. Third, institutional capacity is not yet sufficient to capture the runoff pulses that could offset climate-driven recharge declines. Addressing these challenges can include quantification of mountain block recharge, expanded recharge infrastructure (such as Flood-MAR and high-elevation spreading basins), and stronger incorporation of climate scenarios into SGMA planning. Without these measures, the Sierra Nevada's role as a groundwater recharge engine will become increasingly compromised under future warming.

DROUGHT

Drought remains one of the most consequential climate hazards for the Sierra Nevada and the downstream regions that rely on its water. While reduced snowpack has long been recognized as a driver of drought vulnerability, new research shows that the impacts extend far beyond simple reductions in snow storage. Warming temperatures accelerate snowmelt and shift precipitation toward rain, which reduces the persistence of spring runoff and diminishes the capacity of the Sierra to buffer California's Mediterranean climate pattern of wet winters and dry summers (Siirila-Woodburn et al., 2021; Mote et al., 2018). This shift translates directly into reduced reservoir inflows during summer and fall, declines in late-season streamflow, and constrained groundwater recharge opportunities (Hatchett et al., 2022; Rhoades et al., 2022).

Quantitative projections under CMIP6 scenarios provide clearer estimates of how these processes will intensify drought. Multi-model ensembles indicate that by mid-century, SWE in the Sierra could decline by half, with runoff volumes reduced as well (Rhoades et al., 2022). By late-century under high emissions scenarios, runoff reductions exceed and the shift toward earlier flows significantly curtails infiltration into aquifers. Hydrologic modeling shows that these changes translate to reduced carryover storage in some key reservoirs, which in turn could lower the capacity to meet dry-year demands in the downstream Central Valley (Knowles et al., 2018).

Beyond snowpack loss, drought severity is increasingly shaped by warmer temperatures and higher evaporative demand. Research on the recent 2012–2016 and 2020–2022 droughts shows that high temperatures amplified soil moisture deficits, increased vegetation water stress, and accelerated depletion of surface and groundwater supplies, producing conditions sometimes termed as "hot droughts" (Williams et al., 2020; Diffenbaugh et al., 2015). Both the frequency and duration of these hot droughts are expected to increase, with late-century scenarios showing multi-year droughts becoming twice as likely compared to the historical period (Cowan et al., 2020; Swain et al., 2018).

Regional differences in vulnerability are also important. Northern Sierra basins, which are most sensitive to rain-snow transitions, show the largest declines in summer runoff, while higher elevation Southern Sierra catchments retain more snow but still face compressed melt seasons and higher evaporative losses. These dynamics mean that agricultural regions of the Sacramento Valley may face stronger reductions in surface-water deliveries, while some southern Central Valley districts may be more buffered by higher-elevation sources but increasingly dependent on groundwater pumping to bridge supply gaps (Liu et al., 2022).

The impacts of drought in the Sierra Nevada extend directly to agriculture, ecosystems, and urban water supplies. For agriculture, reduced allocations from the State Water Project and Central Valley Project during recent droughts forced greater reliance on groundwater, leading to overdraft and land subsidence in several subbasins (Liu et al., 2022). For ecosystems, diminished summer streamflow has reduced habitat for cold-water fisheries such as salmonids, while prolonged low-flow conditions increase stream temperature and degrade water quality (Asarian et al., 2023). Reduced low-flow and the loss of perennial stream habitat to intermittent conditions is expected to show up as another climate stressor to aquatic habitat (Herbst et al., 2019). For urban areas, cities dependent on Sierra Nevada reservoirs experienced mandatory restrictions and conservation orders during the most recent droughts, underscoring the limits of storage infrastructure under more volatile hydrology (Swain et al., 2018).

Taken together, these findings illustrate that drought in the Sierra Nevada is no longer just a matter of precipitation deficits. It is increasingly a compound hazard driven by warming, declining snowpack, earlier runoff, and higher evaporative demand. Projections suggest that these vulnerabilities will grow more severe by mid-century and intensify further by late-century under high-emissions scenarios. The consequences will be felt not only within the Sierra Nevada itself, but across California's agricultural heartlands, ecosystems, and urban centers that depend on the region's water. Addressing these risks will require integrated strategies that link snowpack monitoring, reservoir operations, MAR, and demand-management to prepare for a drier and hotter future.

WATER QUALITY

Water quality in the Sierra Nevada is increasingly at risk from climate-driven changes in snowpack, runoff, drought, and wildfire. Warmer conditions and declining snowpack reduce dilution capacity in rivers and reservoirs, concentrating pollutants and raising stream temperatures during the summer low-flow season. During droughts, low flows can often coincide with high air temperatures, driving up stream temperatures and reducing dissolved oxygen levels, with cascading effects on cold-water fisheries such as salmonids (Asarian et al., 2023). Climate projections show that with longer summer droughts and hotter extremes, these stressors will intensify throughout the century (Williams et al., 2020).

Earlier snowmelt and shifts toward rain not only change runoff timing but also alter the flushing of pollutants and nutrients. Mid- to late-century conditions of warmer temperatures along with earlier snowmelt could translate into higher summer concentrations of nutrients and organic matter, raising the risk of harmful algal blooms (HABs) in major foothill reservoirs (Ralston & Moore, 2020; Moore et al, 2008). Observations from Folsom reservoir and many other Californian inland water bodies already show HAB outbreaks that align with drought years, earlier runoff, and higher evaporation (Richardson, 2025; Robbins, 2021).

Wildfire represents one of the largest and fastest-growing threats to Sierra Nevada water quality. As fire seasons lengthen and high-severity burns become more common (Williams et al., 2023), watersheds face greater post-fire erosion and sedimentation risks (**Box 3.4**). Intense storms in burned basins mobilize large quantities of ash, fine sediment, and soil nutrients, which are then delivered into downstream rivers and reservoirs. These inputs spike turbidity, raise treatment costs, fill reservoir storage capacity, and destabilize aquatic habitats (Brucket et al., 2025; Hacker, 2015).

Box 3.4: *Post-Fire Erosion and Sediment Impacts on Sierra Nevada Water Quality*

Wildfire is emerging as one of the most severe water quality threats in the Sierra Nevada, not only because of the immediate loss of vegetation and soil cover, but also due to the cascading impacts of post-fire erosion. High-severity fires create hydrophobic soils and expose bare slopes, which dramatically increase runoff and sediment transport during subsequent storms.

Following the 2014 King Fire in the El Dorado National Forest area, sediment delivery to streams increased more than fourfold compared to pre-fire conditions, with turbidity spikes disrupting downstream water treatment operations (Ewell et al., 2014; Bland, 2017). More recently, the 2021 Caldor Fire burned over 220,000 acres of the central Sierra, and rainfall in its aftermath triggered severe debris flows and sediment pulses, raising turbidity levels in many downstream reservoirs, forcing emergency monitoring by local water utilities (Ellsworth & Stamer, 2021; East et al., 2025).

Climate change is projected to increase the likelihood of such cascading events. Warming temperatures and drier summers lengthen fire seasons and promote high-severity burns, while more intense winter storms, including atmospheric rivers, can mobilize vast amounts of fire-generated ash and sediment (Albano et al., 2017). Together, these shifts suggest that post-fire sediment loads into Sierra reservoirs may become more frequent and more severe, reducing reservoir storage capacity, elevating treatment costs, and degrading aquatic habitats.

Mitigation measures such as forest restoration to reduce fire severity, rapid deployment of erosion control practices (e.g., mulching, contour felling, re-seeding), and investments in post-fire watershed recovery programs will be increasingly critical to protect water quality in the Sierra Nevada.

Groundwater quality also faces indirect vulnerabilities. Reduced recharge from the Sierra could diminish dilution, which can increase pumping to mobilize salts, nitrates, and geogenic contaminants, such as arsenic, in connected Central Valley basins (Haugen et al., 2021). This compounds the stress on both drinking water supplies and agricultural irrigation quality in foothill and valley communities.

Taken together, the Sierra Nevada's water quality vulnerabilities reflect an intensifying combination of stressors: reduced summer dilution flows, increased thermal stress, more frequent HABs in reservoirs, and heightened post-fire erosion and sedimentation. These processes cascade downstream, affecting agriculture, urban supply, and aquatic ecosystems. Proactive strategies such as post-fire erosion control, forest restoration to reduce fire severity, improved HAB monitoring, and integrated surface-groundwater quality management will be essential to safeguard water quality in a changing climate.

WATER DEMAND

Water demand in the Sierra Nevada region is becoming increasingly vulnerable to climate-driven changes in snowpack, streamflow timing, and temperature. Sierra Nevada provides a critical share of California's water storage, ranging from 61–71% of the water stored in reservoirs (Dettinger & Anderson, 2015; Bales et al., 2011). Warming temperatures have also shifted runoff earlier in the year by one to three weeks on average, leading to reduced water availability during the late spring and summer when demand is highest (Beltran-Peña et al., 2015).

These hydroclimatic shifts have increased seasonal pressure on both local and downstream water users. Municipal and agricultural demand typically peaks between May and September, but surface water supplies from Sierra Nevada's snowmelt now diminish earlier in the season, prompting greater reliance on groundwater pumping and reservoir releases. In dry years, this shift intensifies competition among urban, agricultural, and environmental water needs, and

contributes to over-extraction in connected basins such as the San Joaquin Valley, where groundwater levels have dropped by tens of meters over recent decades (Liu et al., 2022).

Future scenarios indicate that continued snowpack loss and warming could further amplify demand pressures. The evaporative water demand in connected basins may rise during extreme dry years, even as natural storage capacity from snow and soil moisture declines. These trends highlight the importance of integrating MAR, meadow and forest restoration, and improved monitoring to maintain seasonal water availability and reduce demand-supply mismatches under a changing climate.

3.2.4 Adaptation Actions

Adaptation strategies in the Sierra Nevada region focus on maintaining ecosystem services, sustaining water supply reliability, and reducing community vulnerabilities as climate pressures intensify. A central pillar of adaptation involves restoring and managing natural infrastructure, including meadows, forests, and riparian corridors. Meadow restoration projects across the Sierra Nevada have increased baseflows, enhanced late-season water availability, and improved drought resilience (Hunt et al., 2018; Loheide et al., 2009; Hammersmark et al., 2008). Forest management practices, including strategic thinning, prescribed fire, and cultural burning led by Tribes, are increasingly used to reduce wildfire risk, reduce evapotranspiration, improve forest structure, and stabilize snowpack retention at mid-elevations (Guo et al., 2025; Shive et al., 2025; Stephens et al., 2018; Saksa et al., 2017; North et al., 2012). Such ecosystem-based approaches deliver multiple benefits by linking hydrologic functions with ecological integrity and carbon storage (Guo et al., 2025).

Water management adaptation is shifting toward integrated surface-groundwater strategies and modernized infrastructure. The California Department of Water Resources and local agencies are advancing MAR, expanding high-elevation snow and soil moisture monitoring networks, and improving forecasting for reservoir operations to address earlier runoff timing (CDWR, 2024; Hanak & Lund, 2012; Null et al., 2010). Infrastructure modernization, including reoperating reservoirs to align with changing hydrologic regimes, is a key strategy for maintaining summer water availability. Coordinated conjunctive use and recharge projects are emerging across the Sierra foothills and adjacent basins to buffer against seasonal supply-demand mismatches.

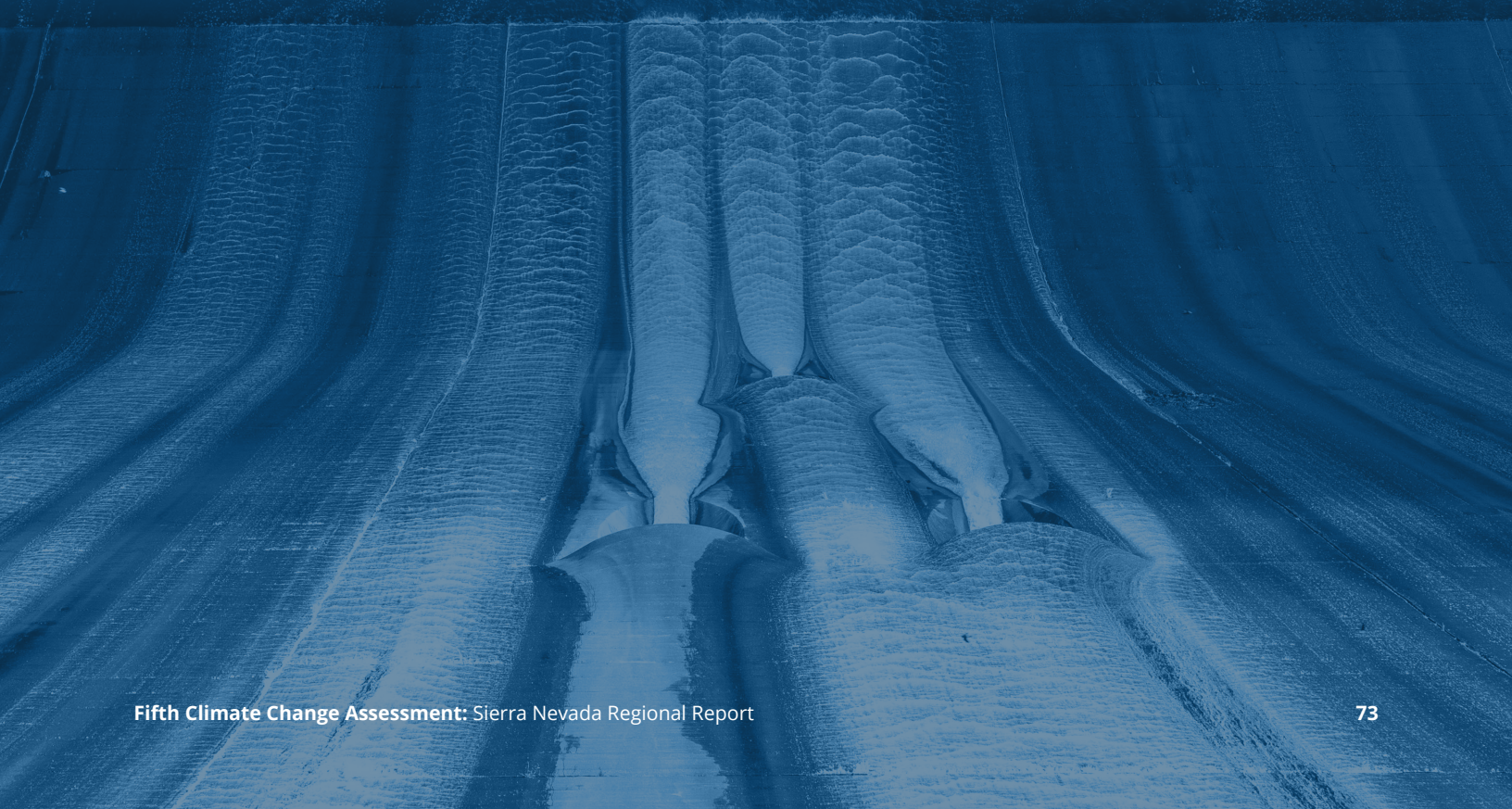
Tribal and community-led adaptation is also gaining momentum. Indigenous land stewardship, including cultural burning and riparian restoration, is being restored through collaborative agreements that repair fire regimes and support ecosystem health (Lake et al., 2024; Lake et al., 2017). Tribal Ecological Knowledges are informing forest and watershed management through partnerships with state and federal agencies. In parallel, rural communities and water districts are investing in drought contingency planning, emergency water supply diversification, and forest fuel reduction to protect water infrastructure and ecosystems (Soderquist, 2021).

Despite these advances, adaptation gaps persist. Climate change is not only limiting the water supply but it is also exposing structural limitations in the legal and regulatory infrastructure governing water allocation. Western water rights systems were largely designed under assumptions of climate stationarity (i.e., past observations can reliably predict future conditions), with diversion rights tied to historic seasons of runoff and water demand. As warming reduces

snowpack, shifts runoff to earlier, and lengthens dry summers, water may no longer be available during the legally defined season of diversion, leaving some rights holders unable to access water when they are entitled to use it. At the same time, riparian users, whose rights depend on natural river flow rather than stored water, may face declining late summer water availability under most climate scenarios. These shifts highlight that adaptation must address not only physical infrastructure but also the legal and institutional frameworks governing water allocation, timing of diversion, and instream flow protection under changing hydroclimatic conditions (Bork & Mensik, 2023). There is also a need to scale up meadow and forest restoration across entire watersheds, expand real-time snow and soil monitoring, integrate climate projections more directly into regional water allocation and land management plans, and secure long-term funding to support Tribal and community adaptation leadership. Effective adaptation will require coordinated watershed-scale approaches that link ecosystem restoration, water management, and community resilience across jurisdictional boundaries.

Chapter 4.

Built Systems



Key Message

The Sierra Nevada region's critical infrastructure, including its vast water conveyance, reservoir, energy, and transportation systems, is increasingly vulnerable to climate extremes like wildfire, floods, and drought. Aging dams and roads are strained by the "climate whiplash" of extreme precipitation and drought. Wildfire directly threatens energy generation and transmission, creating compounding risks such as power shut-offs, debris flows, and supply disruptions. To safeguard these essential services that support both local communities and the entire state, a fundamental shift is required from static, historically-based management to dynamic, climate-informed resilience strategies. This includes modernizing reservoir operations with forecast-informed systems, expanding managed aquifer recharge, and investing in hardened infrastructure like underground transmission lines and slope stabilization to withstand the escalating pressures of a changing climate. Infrastructure that is resilient to climate threats, combined with long-term investments in projects designed to address future challenges, will strengthen climate resilience across the region.

4.1 Introduction

Infrastructure in the Sierra Nevada is embedded within a region of diverse topographies and climatic variability. The region encompasses extensive systems of roads, reservoirs, hydroelectric facilities, water conveyance networks, and power transmission infrastructure, many of which serve both local communities and broader statewide needs. Early infrastructure projects in this region, such as the completion of the transcontinental railroad through the Sierra Nevada in 1868 and the creation of the Hetch Hetchy Reservoir in 1923 (Hanson, 2005), pre-date modern understanding of climate variability, presenting both systemic vulnerabilities and strengthening the need for climate-resilient design and management strategies. Observations and modeling indicate increasing frequency and intensity of wildfire, extreme precipitation, and drought, which place both physical and operational stresses on infrastructure. This region hosts a complex mix of interdependent federal, state, and local water and power systems which are both increasingly vulnerable to projected climate extremes and critical to improving climate resilience across the region.

4.2 Vulnerability

4.2.1 Reservoirs and Conveyances

California's reservoir and water conveyance systems underpin the state's water security, energy production, and flood management capacities. Historically, these systems were designed and managed based on 20th-century hydrologic records, which often fail to capture the variability and extremes projected under current climate trends. Climate modeling indicates intensified *climate whiplash*, the abrupt oscillation between extreme weather conditions, will increasingly challenge reservoir operations caught between the opposing objectives of flood control and water storage.

Since the Fourth Assessment, observations suggest that the capacity of existing dams and reservoirs to reliably store and manage water has not improved in line with evolving climate pressures. An overwhelmingly wet winter in 2022 and spring in 2023 brought a series of atmospheric rivers that simultaneously ended a multi-year drought while challenging flood control systems. Research indicates that atmospheric rivers are becoming larger and more frequent under observed warming, suggesting that existing storage and flood management infrastructure may be increasingly pushed beyond their operational design limits (Henny & Kim, 2025; Purohit, 2024). Aging dam structures, limited flood control capacity, and insufficient conveyance infrastructure to capture and direct excess runoff highlight persistent infrastructure gaps. These gaps reduce the system's flexibility in responding to both droughts and extreme precipitation events, underscoring the need for modernization and adaptation.

Existing infrastructure based on historic hydrological patterns will likely face challenges when it comes to a more dynamic future climate. For example, hydropower generation, traditionally considered a reliable and flexible energy source, is vulnerable to more variable and unpredictable runoff patterns. As snowpack reliability declines and precipitation shifts from snow to rain, the alignment of water availability and electricity demand becomes increasingly misaligned, undermining hydropower reliability and efficiency. To mitigate these challenges, emerging strategies for enhancing California's water resilience may be adopted, including expanding off-stream reservoirs, increasing MAR capacity, and improving water conveyance to effectively distribute excess runoff to recharge sites rather than relying solely on traditional reservoir storage.

4.2.2 Roads

Transportation infrastructure through mountainous regions like the Sierra Nevada is increasingly susceptible to climate-related events. Intense precipitation, especially on fire-scarred landscapes, can induce high-magnitude debris flows and landslides, damaging critical infrastructure including roads, trails, culverts, and bridges (Keller et al., 2021). In 2021, the Dixie Fire devastated the Feather River Canyon, a critical watershed that supplies a majority of the water for the State Water Project (Taylor et al., 2022). This occurred during the hottest summer on record and after two consecutive years of severe drought (CDWR, 2021). Low precipitation, diminished snowpack, and dry soils, along with excessive fuel buildup, primed the landscape for intense burning and extreme post-fire erosion. Following the fire, intense precipitation triggered high-magnitude debris flows and landslides from the Dixie Fire burn scar, destroying numerous bridges, culverts, and trail networks, as well as rendering Highway 70 impassable for an extended period of time.

The region's steep terrain, coupled with the frequency of high-intensity storms and prolonged fire seasons, continues to threaten the stability and reliability of critical transportation corridors. While climate change is expected to exacerbate risks from wildfire and flooding, one modest offsetting effect may be fewer seasonal closures due to snow, potentially improving road and rail access during winter months in some years. However, this benefit is outweighed by the projected rise in wildfire intensity and more frequent extreme storm events, which amplify disruptions to road and rail networks across the Sierra Nevada and increase the need to invest in climate-resilient infrastructure to safeguard regional transportation networks.

4.2.3 Energy Infrastructure

The Sierra Nevada region generates power primarily through hydroelectric facilities which are operated not only by federal agencies such as the United States Bureau of Reclamation (USBR) (e.g., Shasta, Folsom, Trinity, and New Melones Dams), but also by major utilities including PG&E, Southern California Edison (SCE), and the San Francisco Public Utilities Commission's Hetch Hetchy system. Together, these public and private systems supply a substantial share of California's hydropower, supporting both the regional and statewide grid. In addition, the State Water Project and numerous smaller water and power districts operate reservoirs and generation facilities throughout the Sierra Nevada, further contributing to the region's energy portfolio. While solar and wind facilities are not yet present in the Sierra Nevada at the scale observed in California's desert or coastal regions, distributed solar adoption is increasing in foothill communities, providing some localized diversification of supply. Forest biomass projects, such as Sierra Pacific Industries in Plumas County and Heartwood Biomass Project in Tuolumne County, also supplement generation capacity, though they do not substantially reduce grid vulnerability to climate extremes.

Energy infrastructure in the Sierra Nevada faces multiple stressors from climatic extremes: the physical threat of wildfire to generation and transmission systems, surging electricity demand driven by continued warming and intensifying heat extremes (ASCE, 2025; Force, 2019), and a regulatory environment that is becoming increasingly incompatible with management in a changing climate (e.g., time frames of Federal Energy Regulatory Commission [FERC] licenses). Wildfire risk has led utilities to implement preemptive power shut offs to reduce ignition potential during extreme weather, but such actions impose cascading costs on communities and critical services (CPUC, 2019). Beyond transmission lines, wildfire hazards during active fire events also pose safety risks to staff and facilities and jeopardize the integrity of the hydropower infrastructure itself. Large woody debris washed into reservoirs from burned watersheds can obstruct intakes, damage penstocks, and impair turbines, creating operational challenges and costly repairs (Wasklewicz et al., 2023). Meanwhile, high summer temperatures drive peak electricity demand for cooling, often coinciding with fire-related transmission outages or generation disruptions. These interacting stressors have increased the risk of rolling blackouts, underscoring the vulnerability of the regional grid to both hydrologic variability and wildfire disturbance.

4.3 Adaptation Pathways for Climate-Resilient Infrastructure

Infrastructure adaptation in the Sierra Nevada necessitates a shift from static risk management toward more dynamic, climate-informed resilience planning. Recent advances such as Forecast-Informed Reservoir Operations (FIRO) illustrate how water management agencies are evolving. FIRO is a reservoir operations strategy that improves real-time reservoir management and enhances flood control and water supply optimization by dynamically adjusting reservoir operations to forecasted hydrological data (Delaney et al., 2020). It is being deployed across the Sierra Nevada and the broader western United States. The United States Bureau of Reclamation (USBR) has incorporated FIRO principles into operations at Folsom Lake, in coordination with the US Army Corp of Engineers (USACE). Similarly, Lake Oroville, New Bullards Bar, and Don Pedro

Reservoir are implementing FIRO approaches, moving beyond strict adherence to historical water control manuals. These collaborative efforts by local agencies, utilities, and federal partners (including PG&E, SCE, and Hetch Hetchy water and power operators) demonstrate the expanding scope of FIRO in enhancing both flood protection and water supply reliability.

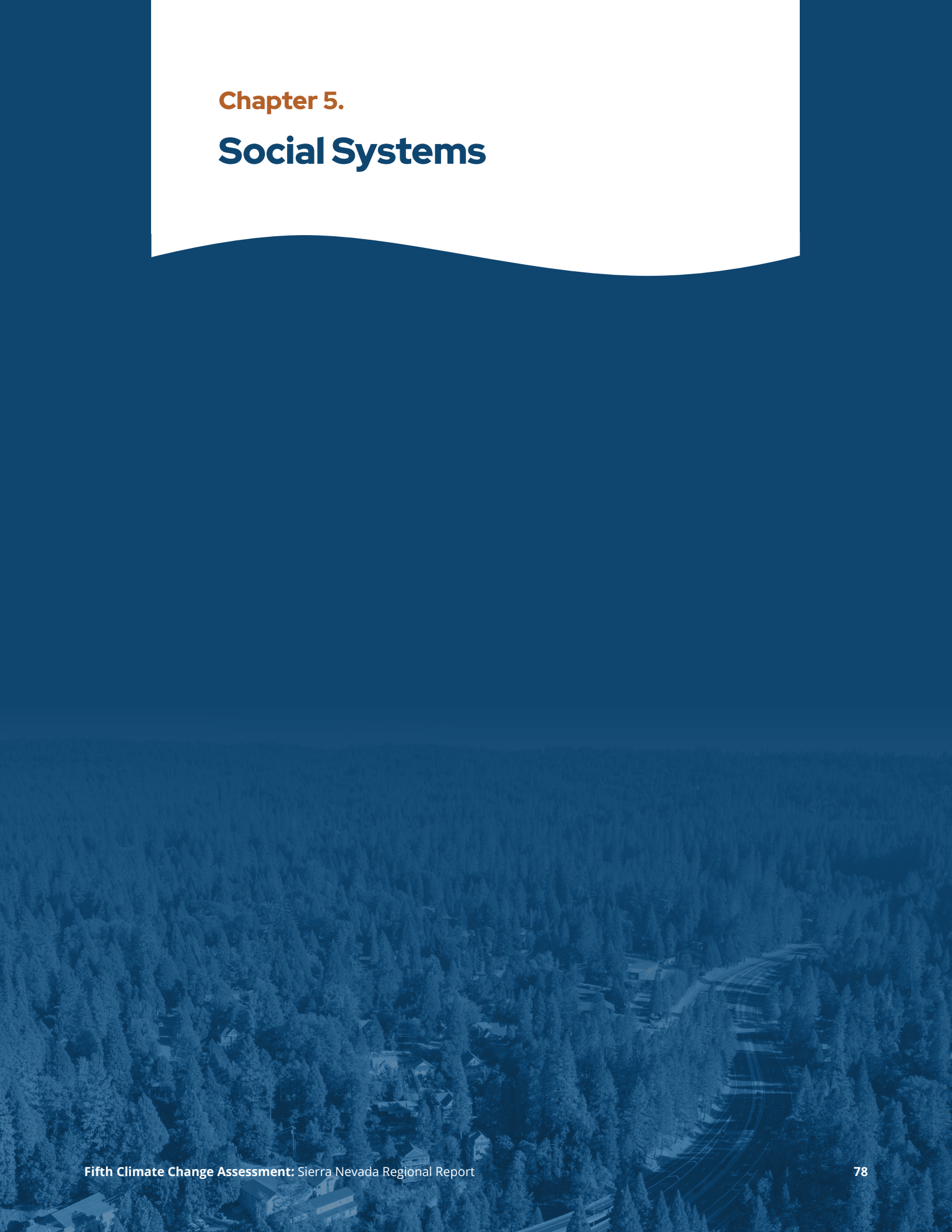
In parallel, new infrastructure projects are advancing anticipatory strategies that complement FIRO. A notable example is the planned Atmospheric River Control (ARC) Spillway at New Bullards Bar Dam, a major initiative of the Yuba Water Agency in 2023. The ARC Spillway will provide operators with flexibility to manage large inflows more proactively, particularly during atmospheric river events. While beneficial even under traditional operating rules, its utility is magnified in the context of FIRO and in a future characterized by greater volatility.

Beyond flood management, water conservation and groundwater sustainability represent equally critical adaptation pathways. The Sierra Nevada is a headwaters region that supplies much of California's developed water supply, and conservation measures will be central to reducing demand pressures under warmer conditions. Additionally, MAR is gaining recognition as a promising strategy to mitigate summer water shortages driven by earlier snowmelt and declining snowpack. MAR has the potential to store high winter and spring runoff for use later in the dry season (Ferencz et al., 2024; CDWR, 2017). However, significant infrastructure gaps remain, including limited conveyance capacity to move high-flows to recharge sites, inadequate surface spreading basins, and insufficient monitoring and permitting frameworks. Streamlining permitting for flood-MAR and advancing research on how diversion of high-flows affects river ecosystems will be essential to ensure recharge expansion does not compromise ecological function or instream flow needs. Investments could include expanding inter-basin conveyance networks, constructing or retrofitting recharge basins and infiltration galleries, scaling on-farm recharge systems, and deploying advanced monitoring and control technologies to maximize recharge efficiency while safeguarding groundwater quality. Statewide initiatives also shape climate-resilient infrastructure planning. The California Department of Water Resources plays a central role through the implementation of the SGMA, which requires local agencies to develop and implement plans to bring groundwater basins into long-term sustainability. Efforts like these encourage alignment of local projects, such as FIRO, Atmospheric River Control Spillways (also known as, ARC spillways), MAR, and conservation programs, with state-level priorities for climate resilience.

Investing in upgrades to existing infrastructure is also critical to the viability of infrastructure in the Sierra Nevada. Ongoing efforts in this region include slope stabilization initiatives for preserving transport and utility corridors in high-relief zones, and modernization of electric grid architecture, including underground transmission lines in fire-prone areas (CNRA, 2018; Rogers-Gibson, 2017). Adaptation of Sierra Nevada infrastructure requires a portfolio approach, which may include modernizing reservoir operations with FIRO, investing in spillway and slope stabilization projects, conserving water resources, and integrating climate science into all planning and permitting. Collectively, these strategies create a more robust, flexible, and adaptive infrastructure system capable of withstanding projected climate changes.

Chapter 5.

Social Systems



Key Message

The Sierra Nevada's predominantly rural and resource-dependent communities, including over 70 Native American Tribes, face profound and disproportionate climate vulnerabilities rooted in their lower-than-state average median incomes, heavy reliance on natural resource- and tourism-based economies, and geographic isolation. These communities are on the front lines of a climate crisis manifesting as more frequent and severe wildfires, which not only cause direct destruction but also trigger cascading crises through public safety power shutoffs, skyrocketing insurance premiums or non-renewals, and prolonged smoke exposure that degrades air quality and public health. Concurrently, the region is experiencing extreme heat events for which mountain communities are unprepared, lacking widespread air conditioning and public health response plans, while the foundational winter tourism economy is undermined by dwindling snowpack and a shorter ski season. Building true resilience requires a multi-faceted approach that includes targeted support for the most vulnerable populations, significant investment in climate resilient infrastructure, and proactive economic diversification through the development of new, sustainable industries like forest biomass products and regenerative agriculture to ensure the long-term viability and equity of these vital communities.

5.1 Introduction

Despite covering one-quarter of the state's land mass, the Sierra Nevada is home to roughly 1.2 million people (just over 3% of California's population) and over 70 Native American Tribes, who have lived and worked within these landscapes for thousands of years. Residents of the Sierra Nevada, and California at large, rely on healthy forests and watersheds for water security, livelihoods, and recreation.

As the climate projections in the previous section show, changing conditions will have wide-ranging impacts on Sierra Nevada, including risks to human and natural communities, cultural practices, and values. It is becoming extremely difficult for Indigenous Peoples to practice cultural burning as a tool for environmental stewardship and food security. Loss of cultural sites during wildfires, drying springs, medicinal plants, and materials used for jewelry, ceremonies, and basketry have already been documented (State of California, 2023a, 2023b). Hotter and more frequent droughts, flooding events, heat waves, and longer and more extreme fire seasons will challenge the ability of communities to sustain essential infrastructure, protect public health, maintain food and water security, and preserve economic and social stability. Most Sierra Nevada residents live in rural communities and are disproportionately dependent on natural resource- and recreation- based economies. These communities face heightened risks, including disruptions to agriculture, forestry, and tourism, as well as reduced access to emergency services and limited resources to recover from climate-related disasters. Strengthening and sustaining rural hospitals and emergency medical access in the Sierra Nevada is critical for addressing growing climate-related health risks, as geographic isolation and declining rural healthcare capacity can limit timely care during extreme heat, wildfire smoke, and other climate-driven hazards.

Additionally, changing climate conditions will have heavy impacts on cultural practices and traditional values across the region. Indigenous practices are being affected through loss of

culturally important species and sites, as well as through disrupted seasonal cycles that affect gathering and ceremonies tied to the predictable timing of snowmelt, plant growth, animal migration, and other cycles. Sierra Nevada Tribes are acting as true stewards of the land despite these impacts by revitalizing cultural burning, meadow restoration, and reclaiming land management authority despite bureaucratic barriers.

The Sierra Nevada's population is defined by connection to place. As the landscape changes, children will grow up in a Sierra Nevada that is vastly different from their parents. Some changes will be due to negative climate hazards like megafires, mass tree mortality from bark beetles and drought, and shifting animal patterns. Other changes will be visual indicators of implemented climate adaptation and restoration efforts. Forest thinning projects, beneficial fire, and other landscape-level efforts will change the population's relationship with the land as places become less familiar and new traditions develop to reflect updated landscapes, seasonal cycles, and accessibility.

The ecosystem services provided by the Sierra Nevada region are vast, supplying much of the state's drinking water, regulating water flows via snowpack runoff, storing carbon in forests and mountain meadows, and many more. One study evaluating the ecosystem services provided by the aggregated lands across Alpine, Mono, and Inyo counties estimated that ecosystem services provide $43.6–$190.9 billion in benefits, largely from carbon storage and water resources (MLTPA, STRI Vulnerability Assessment). These benefits are at high risk to climate impacts, and for a region with an average household income below the state's median (**Table 5.1**), it is critical to evaluate the region's value through nontraditional lenses.

Table 5.1: *Statistics for Counties in the Sierra Nevada*

County	2023 Population (July 1 estimate)	2023 Median Household Income	Persons 65 years+	With a disability, under age 65 years	Percentage of persons age 16 years+ in civilian labor force	Percentage of persons age 25 years + with a Bachelor's degree or higher	2020 Population per square mile
Modoc	8,500	$56,648	30.70%	10.90%	46.00%	23.00%	2.2
Lassen	28,861	$64,395	18.40%	12.50%	39.50%	13.20%	7.2
Plumas	19,131	$64,946	33.00%	12.50%	47.40%	20.50%	7.8
Sierra	3,200	$60,000	32.60%	11.90%	50.40%	24.40%	3.4
Nevada	102,037	$84,905	30.10%	8.70%	53.30%	39.50%	106.8
Placer	423,561	$114,678	21.00%	6.80%	61.00%	42.90%	287.6
El Dorado	192,215	$106,190	24.30%	7.60%	58.00%	38.80%	111.9
Alpine	1,141	$110,781	27.90%	7.50%	59.00%	42.10%	1.6
Amador	41,811	$81,526	28.10%	10.40%	48.00%	22.40%	68.1
Calaveras	46,565	$79,877	29.70%	15.20%	48.40%	22.20%	44.4
Tuolumne	54,204	$72,259	28.70%	14.30%	49.30%	23.90%	25
Mariposa	16,919	$65,378	31.00%	12.30%	54.60%	30.90%	11.8
Mono	13,066	$86,953	19.30%	4.60%	69.70%	34.30%	4.3
Inyo	18,527	$72,432	25.60%	9.60%	56.90%	31.80%	1.9
Madera	162,858	$75,496	14.60%	10.40%	56.10%	17.10%	73.1
Fresno	1,017,162	$71,434	13.20%	9.30%	61.10%	23.90%	169.3
Tulare	479,468	$69,489	12.20%	8.70%	60.50%	15.80%	98.1
Kern	913,820	$67,660	12.20%	8.50%	58.40%	18.60%	111.8

Source: *American Community Survey 5-year estimates 2019–2023, unless another year is indicated. Note that county-wide data has been shown in this table despite Mono, Inyo, Madera, Fresno, Tulare, and Kern counties only having a small geographic portion housed in the Sierra Nevada's Fifth Assessment region.*

5.2 Community Impacts from Climate Hazards

The climate projections described earlier in this report will have direct impacts on Sierra Nevada communities. Sierra communities are uniquely vulnerable to climate change due to their remote locations, lack of communication infrastructure and essential services, and reliance on nature-based economies. Extreme heat, changing precipitation patterns, and wildfires are the climate-driven events most likely to impact Sierra Nevada communities.

5.2.1 Increasing Temperatures and Changing Precipitation Patterns

Higher temperatures are expected across the region, punctuated by periods of summer extreme heat in the lower elevations and hot temperatures in higher elevations that have historically remained temperate through the summer months. Mountain communities, unaccustomed to heat, are largely unprepared for periods of heat in the 80°F and 90°F (26.6°C and 32.2°C) ranges. Jurisdictions lack plans and infrastructure to deal with extreme heat, and few residences and businesses have air conditioning. In the past three years, the Town of Truckee saw an increased

demand for permits to install air conditioning units, with more than 85% of the Town's units being installed between 2020–2023 (Town of Truckee, 2025). Even communities like Sonora, where an average of 75 days a year reach 90°F (32.2°C), are projected to see a 34-day increase in the number of days over 90°F (32.2°C) by the end of the century (from CMIP6 LOCA2 projections; as discussed in Chapter 2). These events will likely strain grid capacity and, in the event of power outages, often lead to longer restoration times for rural communities due to limited resources and accessibility.

Warmer temperatures driven by climate change are altering long-standing precipitation patterns, especially in mountainous regions. Many Sierra Nevada communities depend on snowy winters for both their economies and way of life. Snow supports winter recreation industries like skiing and snowboarding, while also acting as a natural reservoir that slowly releases water in rivers and streams throughout the spring and summer. However, as temperatures rise, more precipitation is falling as rain instead of snow, disrupting these systems. This shift not only shortens the winter recreation season, harming local economies, but also increases the risk of flooding. When rain falls on existing snowpack—known as rain-on-snow events—it can rapidly accelerate snowmelt, overwhelming streams and rivers and leading to dangerous flood conditions. These changes challenge water resource management, threaten infrastructure, and pose serious safety risks to communities downstream

5.2.2 Wildfires

The increasing size, severity, and frequency of wildfires is the primary stressor affecting Sierra Nevada communities, impacting every aspect of the economy and quality of life. As noted in *Section 2.5 Trends in Wildfires*, wildfires are becoming increasingly destructive due to a combination of climate change, fuel buildup from fire suppression and historical forest management practices, and the expansion of the wildland-urban interface (Kosmala-Dahlbeck, 2024). The frequency and intensity of wildfires are projected to continue to rise, exacerbating risks to local economies, public health, and community infrastructure. According to the 2025 Fire Hazard Severity Zones (FHSZ) update from CAL FIRE, approximately a third of the Sierra Nevada region has *high* or *very high* wildfire hazard in state and federal responsibility areas (CalFire, n.d.). Nearly all incorporated cities and towns in the region have *very high* hazard levels in local responsibility areas.

When large, high-severity fires occur, they render vast parts of the state inhospitable at best and uninhabitable at worst, with lasting impacts on local residents. These fires incur billions of dollars in economic loss (Moore Foundation, n.d.), while also compromising the mental, physical, and financial health of affected communities. The record-setting wildfires of 2020 and 2021 resulted in mass evacuations and widespread disruption to the tourism- and resource-based industries that provide the economic foundation of many Sierra Nevada communities. Even the mere risk of wildfire has far-reaching impacts: public safety power shutoffs, the closure of national forests due to extreme wildfire conditions, and the increasing cost of homeowners' insurance are degrading quality of life, disrupting economic activity, and limiting affordability in Sierra Nevada communities (Pauls, 2024).

In addition to broader economic disruptions, climate change is directly affecting household and business finances. At least 40% of households in the Sierra Nevada region live in a county with a median household income below the state's median household income, leaving them

particularly vulnerable to rising costs (USCB, n.d.). As temperatures climb, the need for air conditioning and cooling increases, driving up energy demand—especially during heat waves—while simultaneously reducing the efficiency of the power grid. This combination, along with rate increases, is straining residents' abilities to afford electricity. Power outages—whether due to equipment failure, accidental disruption, or public safety shutoffs aimed at preventing wildfire ignition—have serious consequences, including disruptions to electric-powered medical devices, lost income for businesses and workers, and reduced emergency and general communications (Murphy, 2021).

The growing risk of wildfires have triggered a crisis in the homeowners insurance market. A significant percentage of Sierra Nevada communities lie within CAL FIRE High Hazard Zones (**Figure 5.1**) and face an increased risk of losing insurance coverage. Homeowners are often left with few choices: costly policies, less comprehensive plans, or going without coverage altogether (Little Hoover Commission, 2023). Participation in CAL FIRE-supported Firewise Communities programs provides an important pathway for reducing wildfire risk and strengthening community resilience (NFPA, n.d.).

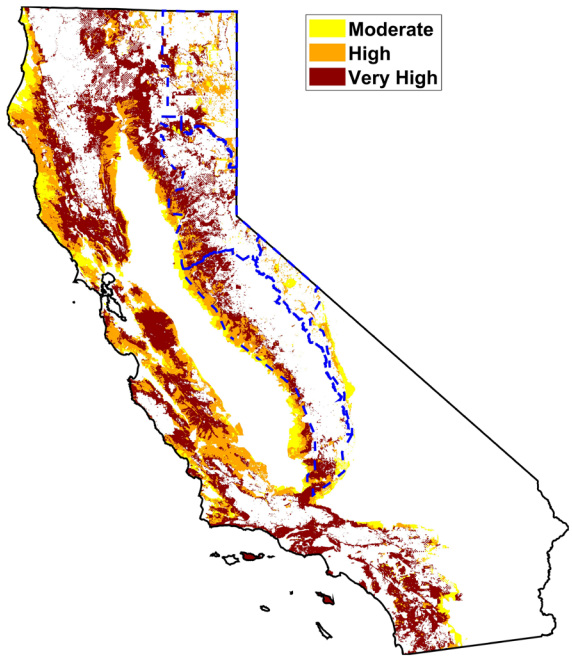


Figure 5.1: *Fire Hazard Severity Zones across California, showing State Responsibility Areas (SRA) effective April 1, 2024, and Local Responsibility Areas (LRA) based on recommended zones from 2007–2011. Fire hazard severity is classified into three categories—Moderate, High, and Very High—which inform land-use planning, building regulations, and wildfire risk mitigation. The dashed outline indicates the Sierra Nevada region within California.*

Wildfires also have tremendous consequences for human health, contributing to prolonged air quality degradation, particularly from smoke and particulate matter (PM2.5), with even brief exposure known to adversely affect health. The aftermath of wildfires further challenges communities through water contamination, increased vulnerability to mudslides, and impacts to mental and emotional health. Vulnerable populations—including people with disabilities, Indigenous communities and people of color, people with limited English proficiency, older adults, and low-income households—are particularly at risk and experience disproportionate impacts from these cascading threats. Beneficial fire—such as prescribed burning or cultural burns led by Tribes—is a critical tool for reducing fuels and wildfire risks. Although these treatments can be managed to minimize smoke exposure, Sierra Nevada communities will need to help residents live with and manage smoke impacts.

The region has developed a more nimble, diverse, and locally driven response to the challenges of mitigating and adapting to climate change at the community level due to an increase in collaborative groups focused on forest and watershed health and wildfire risk reduction; the

continued openness of land management agencies to work with these groups in an institutional framework; and the capacity support provided by new funding streams like the Sierra Nevada Conservancy's Regional Forest and Fire Capacity Program (RFFCP).

5.2.3 Public Health and Healthcare Availability

The Sierra Nevada's population of 1.2 million is at high risk of wildfire smoke exposure, heat-related illnesses, specific injuries or illnesses caused by climate hazards (e.g., injuries obtained while evacuating, lack of household medical equipment or medication during power outages, injuries due to flood or mudslide), and climate-adjacent health impacts related to mental health or community trauma, displacement, economic hardship, and more.

Climate-vulnerable populations are at higher risk of these impacts and may need to seek additional medical care during climate events. Healthcare availability varies across the region, with some populations accessing ample healthcare, and others forced to travel multiple hours to receive general or specialty care. The Southern Inyo Healthcare District is an example of a rural hospital that is the only healthcare provider for a 60-mile radius. Located in Lone Pine and serving over 1 million patients each year, Southern Inyo Healthcare District was almost forced to close in 2025 due to financial strain. Had it closed, there would have been a medical desert with 136 miles to the next hospital serving the Eastern Sierra Nevada (Donohue, 2025).

5.3 Implications for Workforce and Small Business

The economic and workforce implications of climate change in the Sierra region are particularly connected to three industries: forest resilience (including biomass and wood products), regenerative agriculture, and tourism and recreation.

5.3.1 Forest Management and Resilience & New Markets in Biomass and Wood Products

With the increasing frequency of severe wildfires in the Sierra Nevada region (*Section 2.5 Trends in Wildfires*), millions of acres of forests and shrublands could be lost, along with the destruction of several Sierra Nevada communities. In response to the combined threats of wildfire, drought, extreme weather events, and invasive species, the state has committed to treating one million acres each year over the next decade through fuels reduction and forest management (State of California, 2018). One estimate suggests that this effort would double current United States Forest Service (USFS) activity and expand state-funded work by a factor of five (Foye & Field, 2022).

Meeting this goal requires a monumental coordination of policy, environmental review and permitting, workforce training, infrastructure, and market development. An entire supply chain is warranted, including research and development, enhanced wood processing capacity, logistics facilities, biomass energy plants, and markets for new wood products. These developments will create opportunities for small-scale timber operators, local and regional biofuels plants, sawmills, and manufacturing wood products. Many regions lack infrastructure, fuel treatment contractors, trained workers, and permitting capacity. More broadly, there are nascent markets for many wood

products and woody biomass from low-value wood chips and small diameter timber (CalFire, 2023; Heard & Franklin, 2023; Foye & Field, 2022; Go-Biz, 2022; Valley Vision, 2021)

Workforce availability represents another crucial barrier: Several studies indicate workforce gaps among firefighters, foresters, conservation scientists, environmental specialists and technicians, tree fallers, equipment operators, truck drivers, and warehousing technicians (Heard & Franklin, 2023; Foye & Field, 2022; Valley Vision, 2021). Many of these positions face a raft of job quality challenges—low wages and uneven pay between employers, lack of career pathways, poor health outcomes, physical danger, and seasonal insecurity (GAO, 2024; Heard & Franklin, 2023). To address workforce gaps, universities, community colleges, and nonprofits started or scaled up workforce training programs across the Sierra. Over a dozen community colleges are participating in a federally funded Good Jobs Challenge consortium (FoundationCCC, 2022; Valley Vision, 2021), which includes forestry, wildland firefighting, and other forest management workforce training programs (**Box 5.1**).

Box 5.1: *California Jobs First Initiative*

California Jobs First initiative was a landmark planning and investment initiative that applied a triple bottom line approach to making investments in equitable regional economic development. Regions grappled with defining and meeting job quality targets of self-sufficiency wage thresholds in key sectors. Extensive community outreach and planning emphasized bringing historically marginalized Tribal and Latino partners into the process. Three regions encompass the Sierra: the 7-county Sierra region, the 8-county Capital region, and the 10-county North region. Each region created strategies for target industries and foundational capacity to address climate change and strengthen local economies.

Workforce development represented a major focus in the initial Catalyst funding round, with projects developing workforce pathways in firefighting, fuels reduction, sustainable agriculture, and outdoor recreation leadership. Across the regions, Catalyst funds supported feasibility studies, infrastructure planning, and business incubation in key sectors common to the Sierra, including outdoor recreation and tourism, forest management and bioeconomy, and sustainable agriculture and food systems. Additional investments built philanthropic infrastructure, regional business incubators, revolving loan funds, and small business development and entrepreneurial resources to build overall capacity.

For more information, see:
Capital Region We Prosper Together
North State Jobs First
Sierra Jobs First

BIOMASS AND WOOD PRODUCTS

Meeting California's forest management goals is likely to create 5 million dry tons of waste biomass annually (CARB, 2022). Currently, most of the woody byproducts from fuels reduction work are piled and burned, contributing significantly to air pollution and the release of GHGs, jeopardizing the state's air quality and climate goals. Although beneficial fire is a necessary part of the forest management toolkit, meeting California's climate goals will also require the development of viable markets in bioenergy and wood products.

California is investing in scaling infrastructure to utilize the byproducts of forest restoration and fuels reduction work. Entrepreneurial programs have cropped up to support these efforts in the Sierra region including the Sierra Forest Entrepreneurs program led by the Sierra Institute, and the Forest Entrepreneurship Training Bootcamp offered by the Sierra Business Council. These programs offer business plan development, mentorship, public agency procurement support, and

direct support for businesses in fuels treatment, wood product manufacturing, prescribed fire, home hardening, and biomass energy (SBC, 2025; CWDB, 2021).

AGRICULTURE WORKFORCE AND BUSINESS IMPACTS

Climate change will continue to threaten and impact small farms, ranches, and agricultural workers in the Sierra region due to disruptions to water availability, extreme weather events, and wildfire. These disruptions will impact worker health and safety, and may force many to transition to other industries, and potentially other regions. Multiple climate threats such as shifts in precipitation patterns, reductions in snowpack, heat events, and increases in wildfires result in declining crop yields, reductions in groundwater, pest and disease issues, and weed problems (Medellin-Azuara et. al., 2024; PPIC, 2022; Pathak et al., 2018; CalCAN, 2019). **Box 5.2** shows an example of ongoing climate adaptation at a small family farm scale in the neighboring Siskiyou County.

Box 5.2: *Adapting to Change: Small Family Farms in Siskiyou County*

A case study of small, family-run farms in Siskiyou County highlights their vulnerabilities to climate change. These farms face drought and wildfire exposure combined with limited infrastructure and financial resources to mitigate climate-related impacts. Many farmers in the region, as elsewhere in the Sierra, rely on off-farm income to sustain their operations. Despite cultural resistance to explicitly acknowledge climate change, many farmers have adopted adaptation strategies, including diversifying crops, implementing more water-efficient irrigation, increasing water storage, and incorporating organic matter into soils (Peterson-Rockney, 2022a, 2022b).

The study notes that many farmers and ranchers adopted these strategies as emergency responses to weather events. However, such transitions can make returning to prior practices difficult. As a result, the cumulative pressures of climate impacts and operational adjustments have led many to consider supplemental income strategies such as agritourism, reducing herd size, or in some cases, leaving ranching altogether (Peterson-Rockney, 2022a, 2022b).

5.3.2 Tourism and Outdoor Recreation—Climate Change Implications for Regional Economies and Workforce Development

Outdoor recreation and tourism activities play a vital role in rural economies, where extractive industries no longer sustain regional economic growth. Outdoor amenity-rich areas are among the few rural places that have stabilized or increasing populations, (Haggerty, 2019; Olugbenga, 2019 USDOI, 2012; Lawson, 2019; McGranahan et al., 2010; Hunter et al., 2005). However, these regions' successes can threaten to bring urban problems to rural places: housing availability and affordability, traffic congestion, and job quality issues (Visit California, 2025a, 2025b, 2025c; CJF, 2024; SJF, 2024; Valley Vision, 2021; Rumore et al., 2019).

Climate change poses particular risk to the outdoor recreation-based economies of the Sierra region. Outdoor recreation and tourism industries are likely to experience massive operational disruptions and unpredictability due to shifting weather, heat events, natural disasters, and other climate effects. Some destinations will experience declining visitation, while others will see erratic swings that include periods of overcrowding (USFS, 2021; Yanez et al., 2020; NOAA, 2019; Fisichelli et al., 2015). A 2023 study found that every additional 10 degrees increases traffic flows by approximately 1,200 vehicles over two entry points to the Lake Tahoe Basin and leads

to approximately 7,000 additional daily visitor miles of travel (Hui et al., 2023). This may lead to a dramatic influx in tourism during low-elevation extreme heat events. The communities around Lake Tahoe, like many tourism destinations in the Sierra Nevada, are predominantly rural with one-lane roads, limited health care access, and have high fire risk. This influx of visitors leads to traffic congestion, limited evacuation routes, and degradation of public lands. The local communities will need more support and regional planning to handle the trash, sewage, power, parking, and resource constraints during extreme heat events.

Box 5.3: *Integrating Outdoor Recreation with Forest and Wildfire Resilience*

The Mammoth Lakes Trails and Public Access Foundation (MLTPA) led an effort to convene a working group to establish an inter-agency and multi-stakeholder sustainable outdoor recreation strategy on behalf of the California's Wildfire and Forest Resilience Task Force to develop California's Joint Strategy for Sustainable Recreation & Wildfire Resilience. Mono and Nevada Counties have officially adopted the plan as a roadmap and framework for protecting access to outdoor recreation while confronting the increasing threat of wildfires (Mono County California, 2025; Molina, 2025). The strategy contains principles and goals related to integrating forest health with outdoor recreation, enhancing recreation access, promoting public health, and supporting local economies. Some key strategies include:

- Implementing multi-benefit projects in, or adjacent to, the Wildland-Urban Interface (WUI),
- Establishing permanent fuel breaks proximate to recreation trails,
- Prioritizing wildfire risk reduction treatments in outdoor recreation areas.

Certain recreation industries are especially vulnerable: Boating and fishing will be affected by surface water reduction during drought, access issues during early runoffs, low water quality, and eradication of cold-water species (Miller et al., 2022; USFS, 2021). Whitewater recreation, such as kayaking and rafting, may also be affected by altered flow timing and reduced summer discharge, influencing season length, safety, and tourism revenue. Snowpack loss threatens Sierra economies that are dependent on winter sports. Lengths of winter recreation seasons are projected to see reductions of 50% by 2050 and 80% in 2090, resulting in the loss of millions to tens of millions of recreational visits annually by 2050 with an annual monetized impact of hundreds of millions of dollars (Wobus et al., 2017; Fisichelli et al., 2015). Communities that act as gateways to these activity destinations can likely expect less winter season visitation and business revenue losses. Community-led efforts on building a holistic resilience strategy for fuel reductions in forests are underway (see **Box 5.3**).

5.4 Climate Vulnerable Populations in the Sierra Nevada

Understanding the demographic and socioeconomic conditions in the Sierra Nevada region is essential to analyze community-wide risk factors associated with climate change, as well as plan for mitigation and adaptation strategies. While it is difficult to quantify all risk factors faced by every community, several metrics can be utilized to evaluate regional vulnerabilities based on high-risk and disadvantaged populations, and to plan regionally specific resilience measures. The populations most vulnerable to the impacts of climate change include people 65 years of age and older who live alone, 5 years of age and younger, people with disabilities, people living in poverty, households that do not have access to a vehicle or reliable transportation, and those who do not have adequate health or property insurance coverage (**Table 5.2**) (USEPA, 2025; USGCRP, 2016).

Table 5.2 *Social Vulnerability Characteristics of the Sierra Nevada Population by Region*

Characteristic	Sierra Nevada	Sierra Nevada North	Sierra Nevada Northeast	Sierra Nevada South	Sierra Nevada Southeast
Over 65 Living Alone	121,936 (10.5%)	39,723 (13.3%)	2,007 (16.3%)	78,480 (9.4%)	1,726 (12.8%)
Children 5 and Under	227,999 (6,5%)	36,154 (4.7%)	1,883 (4.7%)	188,345 (7.0%)	1,617 (5.1%)
People with Disabilities	445,101 (12.9%)	95,472 (12.5%)	5,970 (18.3%)	339,717 (12.9%)	3,942 (12.5%)
People Living in Poverty	550,002 (16.0%)	59,458 (7.8%)	4,996 (15.4%)	482,179 (18.4%)	3,369 (10.7%)
Households w/o a Vehicle	65,286 (5.6%)	11,859 (4.0%)	725 (5.9%)	51,992 (6.2%)	710 (5.3%)
People w/o Health Insurance	231,578 (6.7%)	30,414 (4.0%)	2,445 (7.5%)	195,897 (7.5%)	2,822 (9.0%)

Source: *US Census, ACS, 2023. Includes full-county data for all full and partial counties in the region.*

Children 5 years of age and younger, as well as adults 65 years of age and older, are more susceptible to heat-related illness, respiratory health issues associated with air pollution and smoke inhalation, and direct injury or displacement due to extreme weather events (USGCRP, 2016). Adults 65 years of age and older who live alone face greater challenges when trying to evacuate during a climate-related emergency (USEPA, 2025).

People with disabilities also face heightened risks due to communication barriers, mobility limitations, and economic insecurity. Emergency communication systems frequently lack the accessible formats that may be necessary for people with disabilities. Extreme weather events may also limit access to life-sustaining medical equipment and cause challenges with evacuation for people with disabilities. In addition, emergency shelters do not always accommodate the accessibility needs of people with disabilities (USEPA, 2025).

Households without access to a vehicle or other means of reliable transportation also face greater risks during evacuations due to extreme weather events or other climate-related emergencies, such as wildfires (USEPA, 2025).

Individuals living in poverty have an increased risk of developing childhood asthma from climate-driven changes in particulate matter and increased ground-level ozone, the largest loss of land to inundation, are the most likely to experience fatal illness from extreme temperatures, and will see the highest rates of labor hour losses due to extreme temperatures (USEPA, 2021).

When rebuilding after disasters, people without sufficient health or property insurance often face barriers in accessing medical care for climate-related health issues, such as heatstroke or respiratory issues that are caused by wildfire smoke or air pollution, and vector-borne illnesses (USGCRP, 2016).

Although overall property and fire insurance coverage has been increasing in the State of California, there were a total of 1,118,422 insurer- and consumer-initiated cancellations and non-renewals of property and fire insurance policies in 2021 (CalDOI, 2022). Nine out of ten counties with the highest exposure to wildfires are in the Sierra Nevada region. These ten counties, despite comprising only 2% of the state's homeowners and dwelling fire insurance policies from the voluntary market, make up almost 22% of the state's FAIR Plan (Fair Access to Insurance Requirements) policies (CalDOI, 2022).

5.5 Knowledge Gaps

The sparsely populated Sierra Nevada presents a significant challenge in tracking demographic and economic trends. Rural communities are spread out over large areas, sometimes with densities as low as 1–2 people per square mile. Traditional demographic and community data sources are usually aggregated at the scale of census tracts, which are too broad to capture local variation. These data limitations complicate efforts to understand local conditions and plan effectively. Small population changes can have substantial impacts on social infrastructure that provides essential services, such as schools, yet may go undetected in standard reporting. As a result, rural communities are at risk of being underrepresented in data that is foundational for making resource allocation and policy decisions.

The economic contributions of these communities are also frequently underestimated. The Sierra Nevada economy relies heavily on the management and health of its natural systems, including forests, oak woodlands, shrublands, lakes, rivers, and meadows. While activities such as forest management, watershed protection, and wildlife conservation generate substantial societal benefits, traditional measures such as Gross Domestic Product (GDP) don't capture the beneficial ecosystem services that stem from effective ecosystem management. Consequently, the work of these communities—while critical to California—is challenging to value appropriately. Valuations of ecosystem services have employed *avoided costs* and *Willingness to Pay* for environmental and conservation measures, including some intangible benefits like aesthetic or pride of place. Such valuations could support decision-making, like converting open space to housing, for example. They are associated with novel policy approaches like Enhanced Infrastructure Finance Districts and markets for carbon sequestration. The challenge lies in accessibility and standardization of such valuations in an applied policy context (Coleman & Machado, 2022; Livingston & O'Connell, 2017).

Conclusion



By the end of the 21st century, long-term warming across the Sierra Nevada is projected to range from approximately 5.4–9.7°F (3–5.3°C) for daily maximum temperatures and 5–9.5°F (2.7–5.2°C) for daily minimum temperatures, compared to the 1981–2010 period. Long-term changes in total precipitation are expected to be relatively modest, generally staying within a 17% increase over the same time-period. However, the intensity, frequency, and sequencing of precipitation events are projected to increase, leading to more frequent droughts and extreme precipitation events. Snowpack is projected to decline substantially across all Sierra Nevada subregions under all emission scenarios, with April 1 SWE projected to reduce approximately 35–77% by mid-century and 53–93% by end-century, altering the magnitude and timing of streamflow and worsening summer dryness. These hydrologic changes are expected to increase drought risk, fire risk, reduce groundwater recharge, and place additional stress on local and statewide water systems. Moreover, projected intensification of winter storms is likely to further challenge water quality, infrastructure, and resource management.

Rising temperatures, shifting precipitation patterns, and reduced snowpack are expected to continue altering the hydrology of the Sierra Nevada. Runoff is projected to occur earlier in the year, summer streamflows are likely to decline, and year-to-year variability is expected to increase. These changes will put additional pressure on water supply systems, ecosystems, and downstream communities. Competition for limited water will likely grow among agricultural, urban, and environmental sectors, while declining surface water availability may increase reliance on groundwater and strain existing infrastructure. Building resilience will require coordinated actions such as adjusting reservoir operations, improving groundwater monitoring and recharge, increasing water use efficiency, restoring headwater meadows and forests to enhance natural storage, and strengthening cross-jurisdictional water management. Implementing these measures, supported by climate-informed planning and data, will be essential to sustain Sierra Nevada water resources in the face of a changing climate.

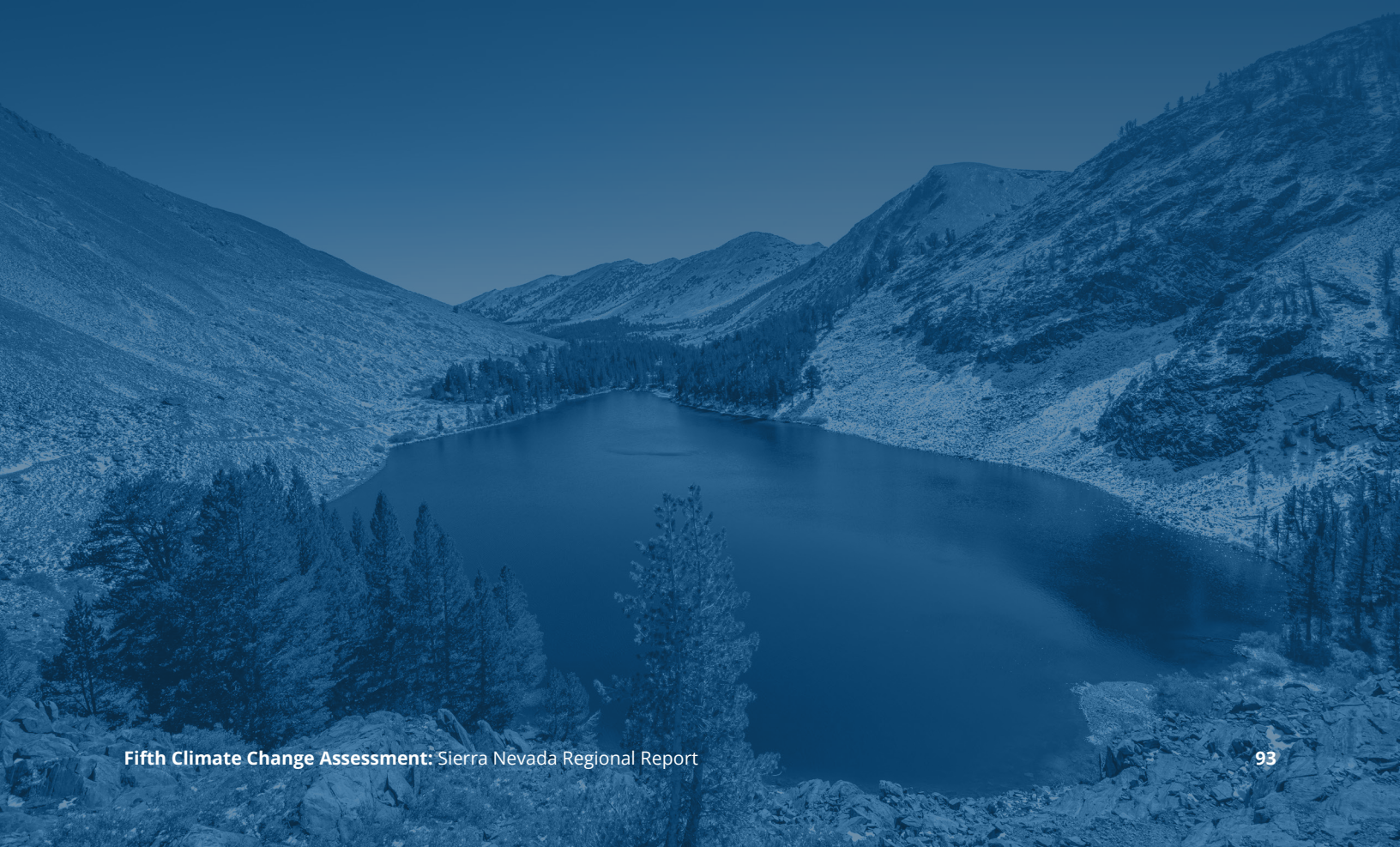
Changes in climate and hydrology will continue to alter Sierra ecosystems, posing challenges for the conservation and maintenance of ecosystem services such as carbon storage. Shifts in species composition, structure, and range will continue, with some species benefiting from a warmer climate, while others will be negatively impacted. The distribution of cover types (forests, woodlands, shrublands, meadows) will likely shift substantially, often driven by amplifying disturbance events, particularly wildfire.

By 2040, the Sierra Nevada is projected to experience more than a 50% increase in wildfire frequency and burned area, depending on GHG emissions. Warmer temperatures, earlier snowmelt, and longer dry seasons are expected to provide ideal conditions for the fire season to start earlier and extend into traditionally wetter months. Increased fuel dryness, especially at mid-elevations where snowpack is declining, may lead to more high-severity fires, threatening conifer forests and promoting shifts toward shrublands and grasslands with lower carbon storage capacity. Novel and creative management approaches will be required to rebalance forest and landscape structure of highly fire-prone (and fire-adapted) ecosystems with 21st-century fire regimes, despite the legacy of 20th-century fire suppression.

The Sierra Nevada's rural communities and economies face growing threats from wildfire, extreme heat, shifting precipitation, and declining snowpack. These stresses will disproportionately impact vulnerable and under-resourced populations. The region's natural resources provide ecosystem services such as water supply, carbon storage, recreation, and cultural values that are vital to California's resilience and prosperity. Prioritizing and advancing community-driven adaptation, workforce development, and collaborative forest and watershed management will be critical to protecting both the people of the Sierra Nevada and the state.

The State of California is already taking significant steps to adapt to climate change and build resilience to growing climate risks. There are statewide initiatives, such as Forecast-Informed Reservoir Operations, proactive forest management, expanded wildfire prevention and fuel reduction programs, and water conservation and groundwater sustainability efforts (e.g., the Sustainable Groundwater Management Act [SGMA])—and investments in climate-resilient infrastructure, that the State is implementing to reduce vulnerability across natural and human systems. Programs that integrate climate information into land-use planning, ecosystem restoration, and emergency preparedness are helping communities manage risks. Together, these actions reflect a proactive shift from reacting to climate impacts toward strengthening long-term resilience for ecosystems, water resources, and communities across the state.

Appendices



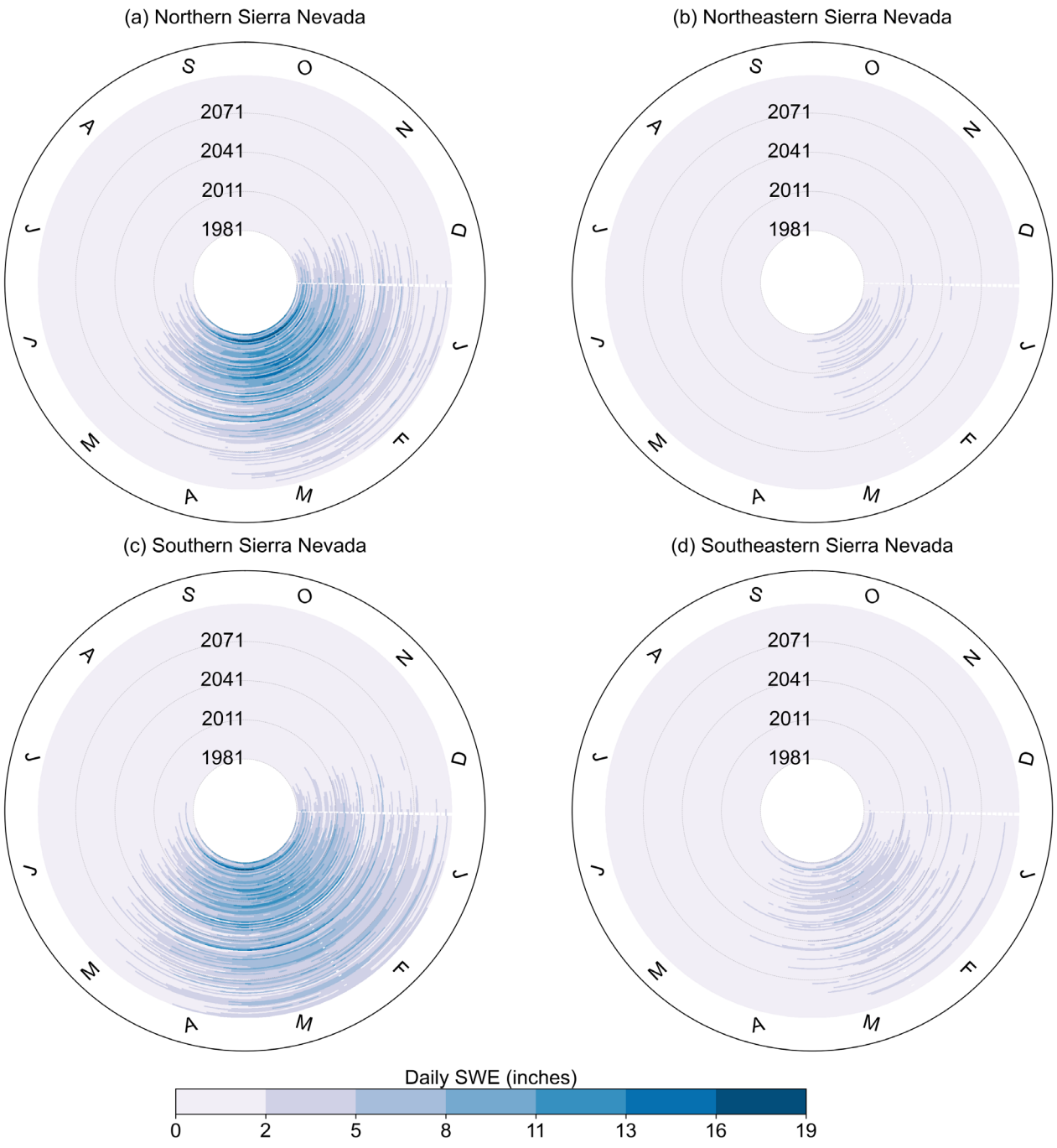


Figure A1: *Daily snow-water equivalent (SWE) in four subregions of Sierra Nevada from 1981–2100. Values are reported as the ensemble mean of 4 GCMs under **SSP 5–8.5**. Panels correspond to (a) Northern Sierra Nevada, (b) Northeastern Sierra Nevada, (c) Southern Sierra Nevada, and (d) Southeastern Sierra Nevada. Circular lines represent daily SWE for each water year (1981–2100), radial lines mark months (October–September), and colors indicate SWE depth.*

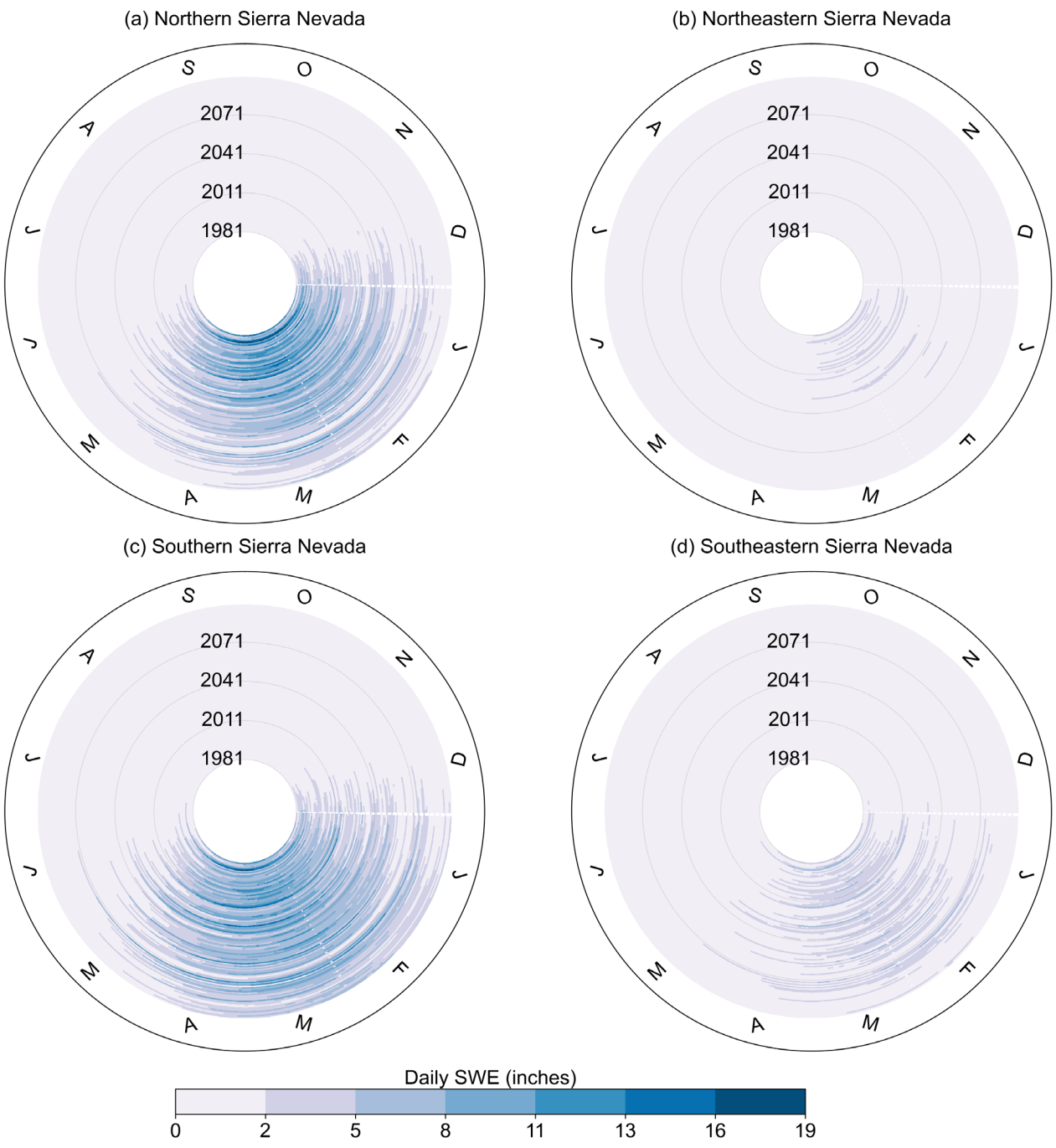


Figure A2: *Daily snow-water equivalent (SWE) in four subregions of Sierra Nevada from 1981–2100. Values are reported as the ensemble mean of 4 GCMs under **SSP 3–7.0**. Panels correspond to (a) Northern Sierra Nevada, (b) Northeastern Sierra Nevada, (c) Southern Sierra Nevada, and (d) Southeastern Sierra Nevada. Circular lines represent daily SWE for each water year (1981–2100), radial lines mark months (October–September), and colors indicate SWE depth.*

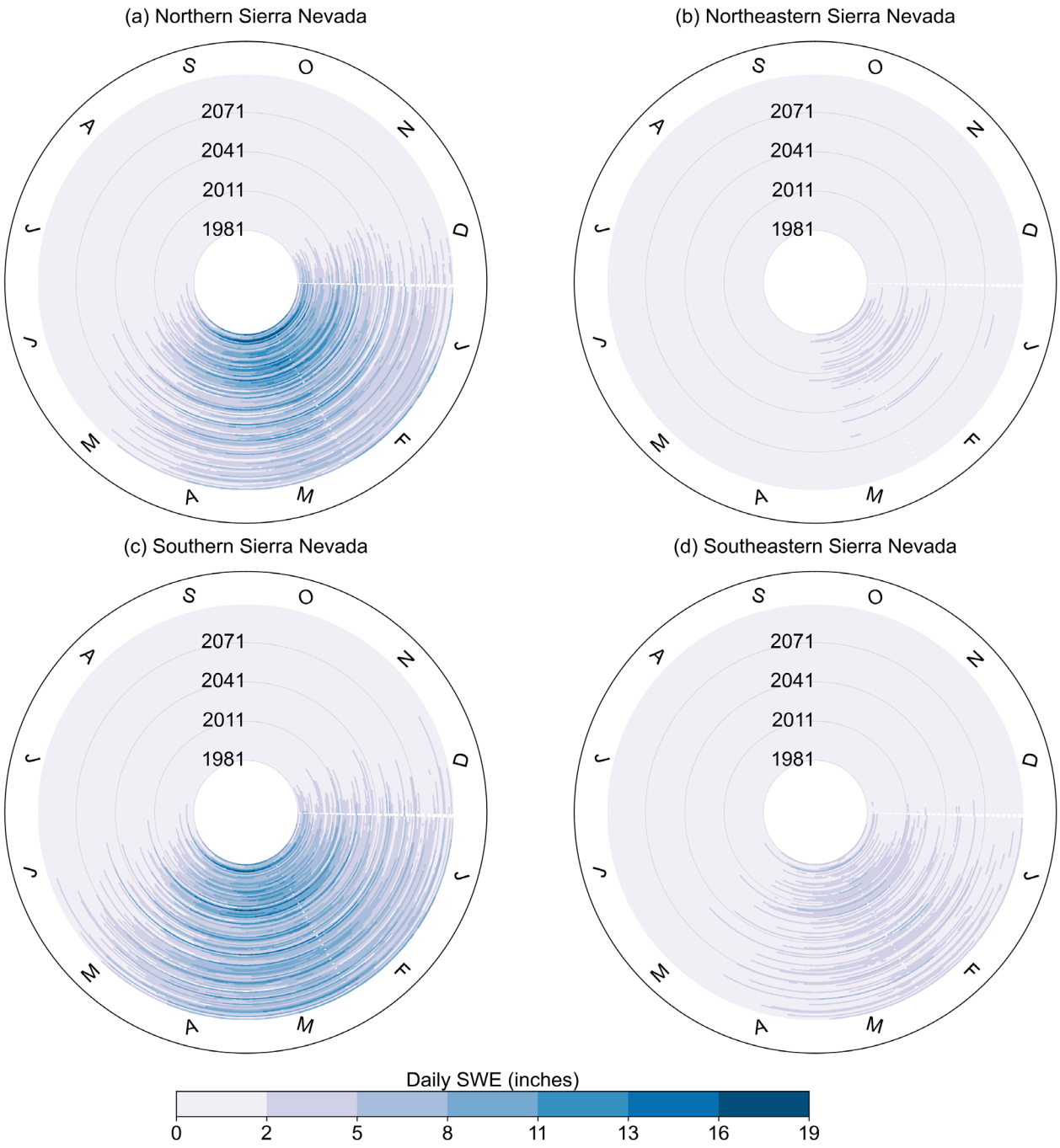


Figure A3: *Daily snow-water equivalent (SWE) in four subregions of Sierra Nevada from 1981–2100. Values are reported as the ensemble mean of 4 GCMs under **SSP 2–4.5**. Panels correspond to (a) Northern Sierra Nevada, (b) Northeastern Sierra Nevada, (c) Southern Sierra Nevada, and (d) Southeastern Sierra Nevada. Circular lines represent daily SWE for each water year (1981–2100), radial lines mark months (October–September), and colors indicate SWE depth.*

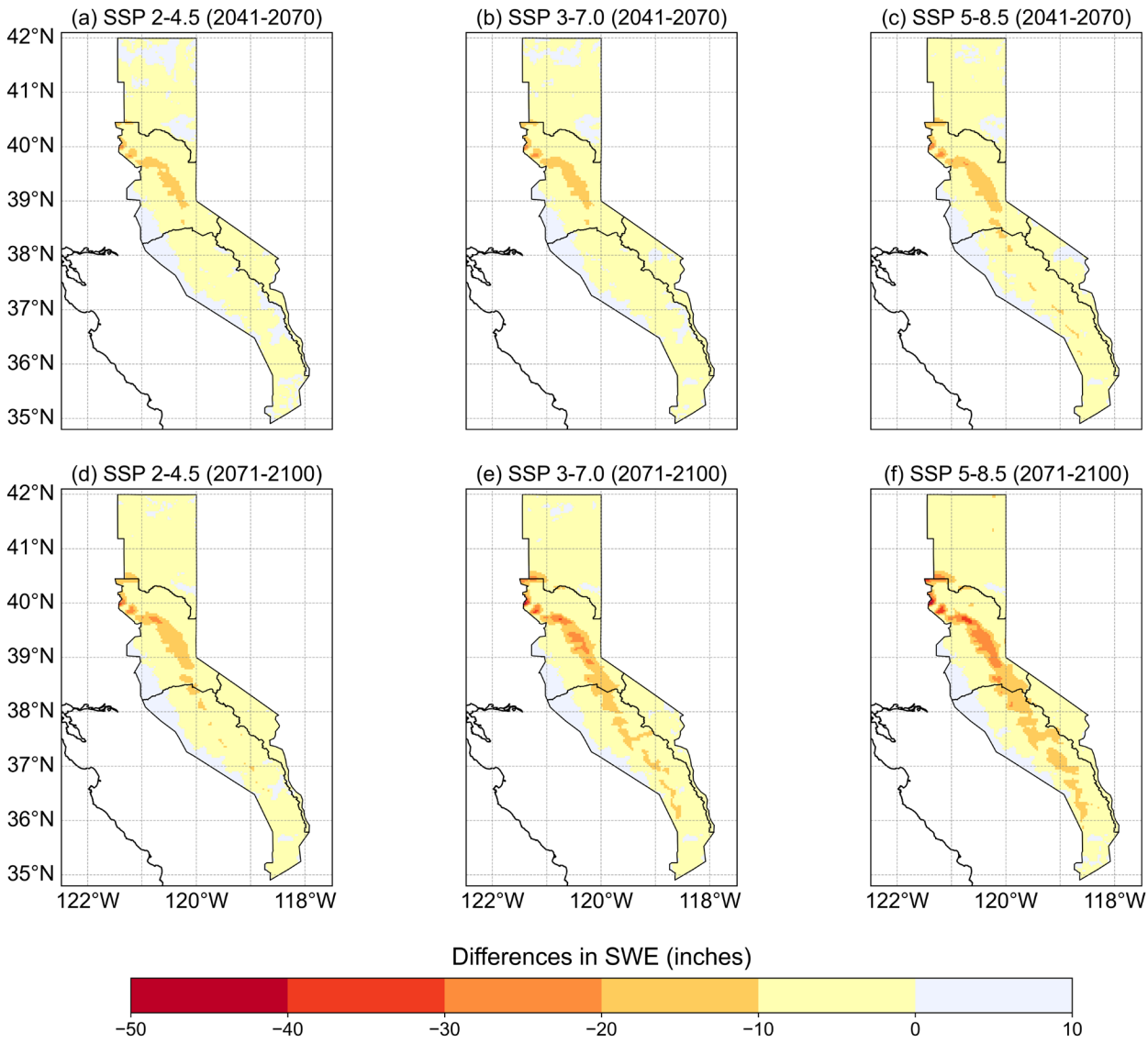


Figure A4: *Projected absolute changes in April 1 snow-water equivalent (SWE), relative to historical mean (1981–2010), for 2041–2070 (a, b, c) and 2071–2100 (d, e, f), under SSP 2–4.5 (a, d), SSP 3–7.0 (b, e) and SSP 5–8.5 (c, f).*

Find **Tables A1-A5** (described below) in the supplemental appendix for the Sierra Nevada Regional Report on the California's Climate Change Assessment website.

Table A1: *Projected changes in maximum (T_{max}) and minimum temperatures (T_{min}) in °F relative to the 1981–2010 baseline for Sierra Nevada subregions and their HUC-8 hydrological basins under SSP2–4.5 (n=33), SSP3–7.0 (n=62), and SSP5–8.5 (n=34). Values represent ensemble mean, standard deviation (SD), minimum (min), and maximum (max) changes (future minus historical) in °F for mid-century (2041–2070) and end-century (2071–2100) periods.*

Table A2: *Projected changes in precipitation (%) in future relative to the 1981–2010 baseline for selected Sierra Nevada subregions and their HUC-8 hydrological basins across SSPs, SSP 2–4.5 (n=33), SSP 3–7.0 (n=62), and SSP 5–8.5 (n=34). Values represent the ensemble mean, standard deviation (SD), minimum (min), and maximum (max) percent changes in precipitation in the future, mid-century (2041–2070) and end-century (2071–2100), periods relative to the historical period (1981–2010) for each basin. Members total indicates the number of climate model realizations included, and Agreement (%) shows the percentage of models projecting a change in the same direction as the ensemble mean.*

Table A3: *Projected percent changes in April 1 snow water equivalent (SWE) relative to the historical period (1981–2010) for Sierra Nevada subregions and HUC-8 hydrological basins across three future emissions scenarios (SSP2–4.5 (n=4), SSP3–7.0 (n=4), SSP5–8.5 (n=4)) and mid-century (2041–2070) and end-century (2071–2100) time periods. Values show ensemble mean (Mean), standard deviation (SD), minimum (min), and maximum (Max) percent changes based on four VIC-model simulations forced by four CMIP6 GCMs.*

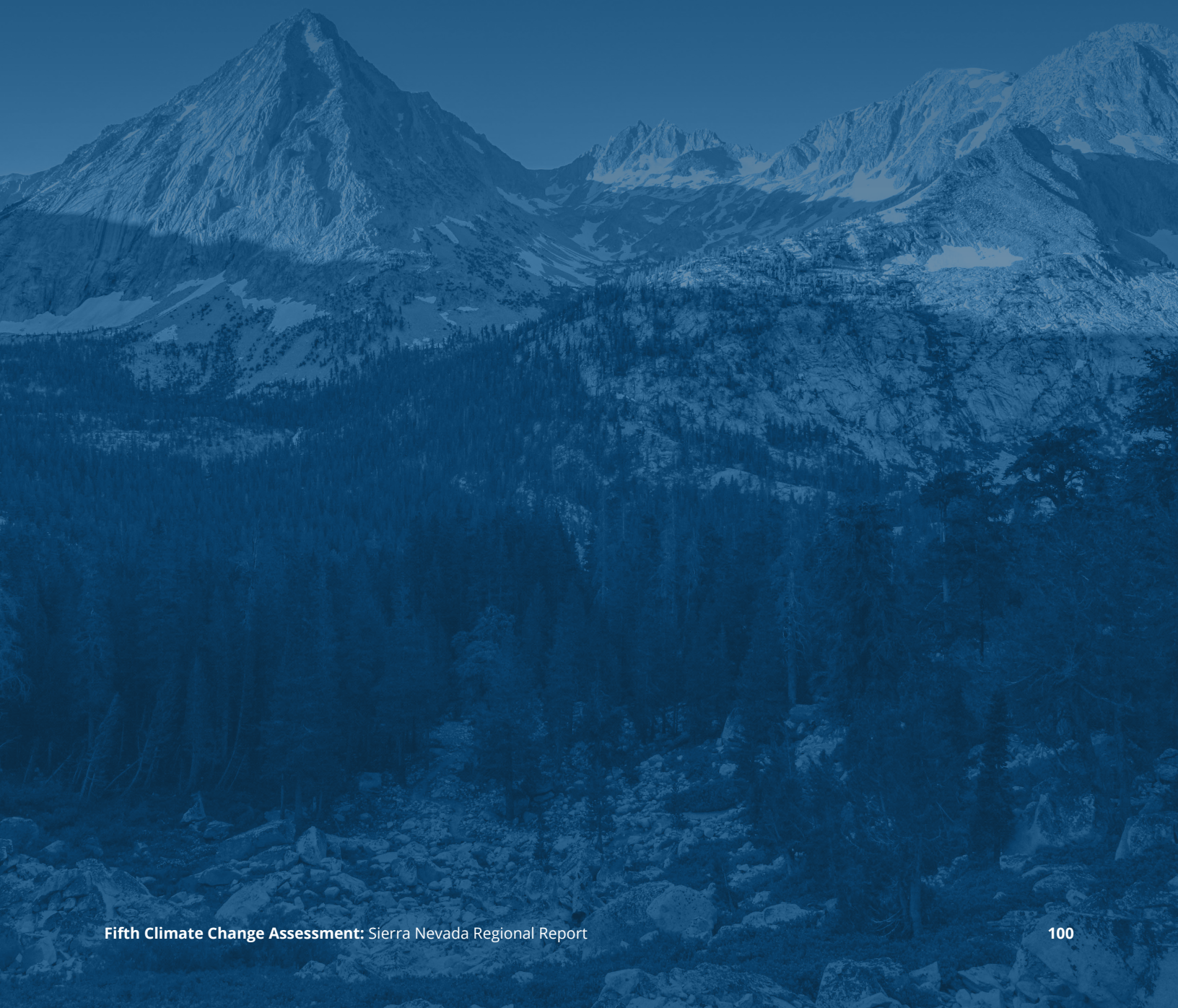
Table A4: *Average projected runoff, reported as the percentage ratio (Future/Historical x 100), for Sierra Nevada subregions and HUC-8 hydrologic basins under three future emissions scenarios (SSP2–4.5 (n=4), SSP3–7.0 (n=4), and SSP5–8.5 (n=4)). Values show ensemble mean (Mean), standard deviation (SD), minimum (Min), and maximum (Max) percent values based on VIC-model simulations forced by four CMIP6 GCMs.*

Table A5: *Projected percent changes in seasonal soil moisture relative to the historical period for Sierra Nevada subregions and HUC-8 hydrological basins across three future scenarios (SSP2–4.5 (n=4), SSP3–7.0 (n=4), SSP5–8.5 (n=4)). Values show ensemble mean (Mean), standard deviation (SD), minimum (Min), and maximum (Max) percent changes based on four VIC-model simulations forced by four CMIP6 GCMs.*

Table A6: *Adaptation Pathways in the Sierra Nevada Using the 5-R Framework*

Intervention Type	Adaptation Actions	Systems Addressed	Localized Context	Implementation Confidence
Resistance	Mechanical thinning and fuels reduction; prescribed and cultural burning to reduce fuel loads and protect forest structure and headwater function.	Terrestrial ecosystems; watersheds; communities	Forested landscapes; higher-elevation forests; Wildland–Urban Interface (WUI) zones; Tribal stewardship areas	High
Resilience	Meadow and watershed restoration to improve hydrologic connectivity, groundwater recharge, flood attenuation, and belowground carbon retention.	Hydrology; ecosystems	Wet meadows; hydrologically connected landscapes; Sierra Nevada headwaters	High
Response	Adaptive reservoir and water-operations planning to address earlier runoff timing and increased winter flows; emergency preparedness for wildfire and extreme events.	Water resources; built infrastructure; communities	Reservoir-dependent communities; Sierra Nevada headwaters; rural towns and WUI communities	Medium–High
Realignment	Transition planning for a shift from snowmelt-dominated to rain-dominated hydrologic regimes; long-term land and forest management acknowledging vegetation type conversion and altered fire regimes.	Hydrology; ecosystems; regional planning	Lower- and mid-elevation landscapes; burn and/or mortality areas experiencing warmer and drier conditions; regions with a greater shift in hydrology; and wildland-urban interfaces	Medium
Reduce	Investing in multi-benefit forest management; lowering wildfire-related emissions and promoting long-term carbon sequestration; lowering fossil fuel consumption and promoting biomass-based energy and hydropower.	Water resources; ecosystem; built infrastructure; communities	Landscapes with high wildfire risks; rural areas for bioeconomy; terrains with high potential of clean energy storage	High

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