Shasta-Trinity National Forest Climate Change Trend Summary

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Summary

The climate of California is in a stage of rapid flux. This document highlights past, current, and projected climate change on the Shasta-Trinity National Forest. It is divided into discussion of historical and current conditions and projected future trends by general resource area. This trend summary is produced by the US Forest Service Pacific Southwest Region (R5) Ecology Program to help forest managers plan for, and where possible, mitigate climate change-related ecosystem vulnerabilities. Climate change trend summaries are currently available for all the National Forests of California and are updated on approximately 5-year intervals as new climate science becomes available.

Climate change has the potential to affect all ecological and socioeconomic components of the Shasta-Trinity National Forest and surrounding areas, as well as other objectives for federal forest managers in this region. Increases in greenhouse gases and temperature, as well as altered precipitation and disturbance regimes (e.g., fire, insects, pathogens, and windstorms), are expected to have profound effects on biodiversity, socioeconomics, and the delivery of ecosystem services over the next century. Adaptation and mitigation are essential to strategic planning for the effects of climate change (Millar et al. 2007). Adaptive management actions at both the stand and landscape scales can reduce vulnerabilities to climate change.

A summary of the most management-relevant trends and projected future changes are outlined in the following table and discussed in greater detail in the text of this report. The trends outlined in the table are specific to northwestern California unless otherwise noted.

Variable	Trend	Projected Future Changes
Air temperature	↑	• 2.2–6.1°C (4.0–11.0°F) increase in annual mean temperature by 2100
Extreme heat	↑	• Significant increase in heat wave frequency and intensity, especially for humid nighttime events and in coastal areas
Marine heatwaves	↑	• Marine heatwaves will drive abrupt shifts in community composition that may persist for years with associated biodiversity loss
Precipitation	↑↓	• -23% to +38% change in mean annual precipitation by 2100 • Shorter, wetter winters and longer, drier summers likely, with higher interannual variability
Snowpack and snowmelt	↓ ←	• 61–100% decrease in April 1 snow water equivalent (SWE) by 2100 • 5–15-day shift towards earlier timing of snowmelt by 2100
Soil moisture and climatic water deficit	↑ ↓	• 4–43% increase in mean annual climatic water deficit (CWD) by 2100 • Reduced soil moisture due to enhanced evapotranspiration
Stream temperature	↑	• 0.4–0.8°C (0.8–1.4°F) increase in August stream temperature by the 2080s
Streamflow volume and variability	↑↓	• General increase in wet season flows and decrease in dry season flows, with overall increase in flow variability • 30–40% decline in the lowest streamflow per decade by 2100
Storms and flooding	↑	• Increased storm intensity and duration, resulting in more frequent/intense extreme precipitation events and flooding • 300–400% increase in the frequency of 200-year floods
Drought	↑	• Drought years twice as likely to occur, with significantly increased risk of prolonged and/or severe drought
Wildfire	↑	• 77% increase in mean annual area burned statewide, and up to 400% increase in montane forested areas of northern California • 50% increase in the frequency of extremely large fires (>10k ha) • Significant increases in fire severity are likely due to more extreme fire behavior combined with human activity and fuel buildup
Vegetation	↑↓	• Distribution of vegetation is generally expected to move upslope and poleward • 2/3 of native flora will experience >80% reduction in range size by 2100 • Increase in tree mortality
Wildlife	↑↓	• Species range shifts due to altered rates of survival and reproduction • Loss of synchrony between reproductive or migratory phenology and resource availability

Table adapted from Hilberg and Kershner (2021b) and data from the 6th IPCC Assessment (IPCC 2022). All trends are local to northwestern California unless otherwise noted.

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Introduction

This summary of climate and climate-driven trends is a product of the Forest Service's Pacific Southwest Region Ecology Program and its partners. We synthesize and summarize current trends and projected future trends related to climate change on the Shasta-Trinity National Forest and surrounding lands in northern California. This analysis is primarily based on local weather station data, PRISM data, Climate Engine, CalAdapt, and published literature; in some instances, important and credible findings from unpublished studies are also included. The summary begins with local and regional trends in temperature and precipitation, then examines how these trends are affecting hydrology, fire, vegetation, and wildlife in the area. A summary of projected future trends in climate and climate-affected resources is also provided. This document provides information of fundamental importance for National Forest management and planning in the face of climate and socioecological change and represents an update of our previous climate trend summary for the Shasta-Trinity National Forest from 2015. Further updates are planned at approximately 5-year intervals.

Local trends in climate over the past century were summarized at the forest level from five local weather stations (WRCC 2022). Stations were chosen based on their geographic location to encompass a range of elevational gradients and on the length and completeness of their records. Records from these sites provide an indication of local-scale variation in climate patterns, and how patterns differ in the extent to which they reflect those seen at the broader forest and regional scales. Descriptions and locations of each weather station used in this report are provided in Table 1 and Figure 1. A detailed descriptions of the methods used in this report can be found in Appendix A.

Table 1. Descriptions of local climate data evaluated for this report, including local weather station and forest data.

Station	Elevation (ft)	Latitude	Longitude	Water year (WY) record	# of missing WYs	Calendar year (CY) record	# of missing CYs	Source
McCloud	3280	41˚15' N	122˚8' W	1910-2003	23	1911-2020	1	WRCC
Shasta Dam	1075	40˚43' N	122˚25' W	1943-2018	6	1944-2020	0	WRCC
Weaverville	1968	40˚43' N	122˚56' W	1916-2018	45	1913-2019	9	WRCC
Whiskeytown	1295	40˚37' N	122˚32' W	1960-2017	8	1961-2020	1	WRCC
Mount Shasta	3590	41˚19' N	122˚18' W	1988-2013	1	1988-2013	1	WRCC
Shasta-Trinity National Forest		-	-	1959-2019	0	1958-2019	0	Climate Engine
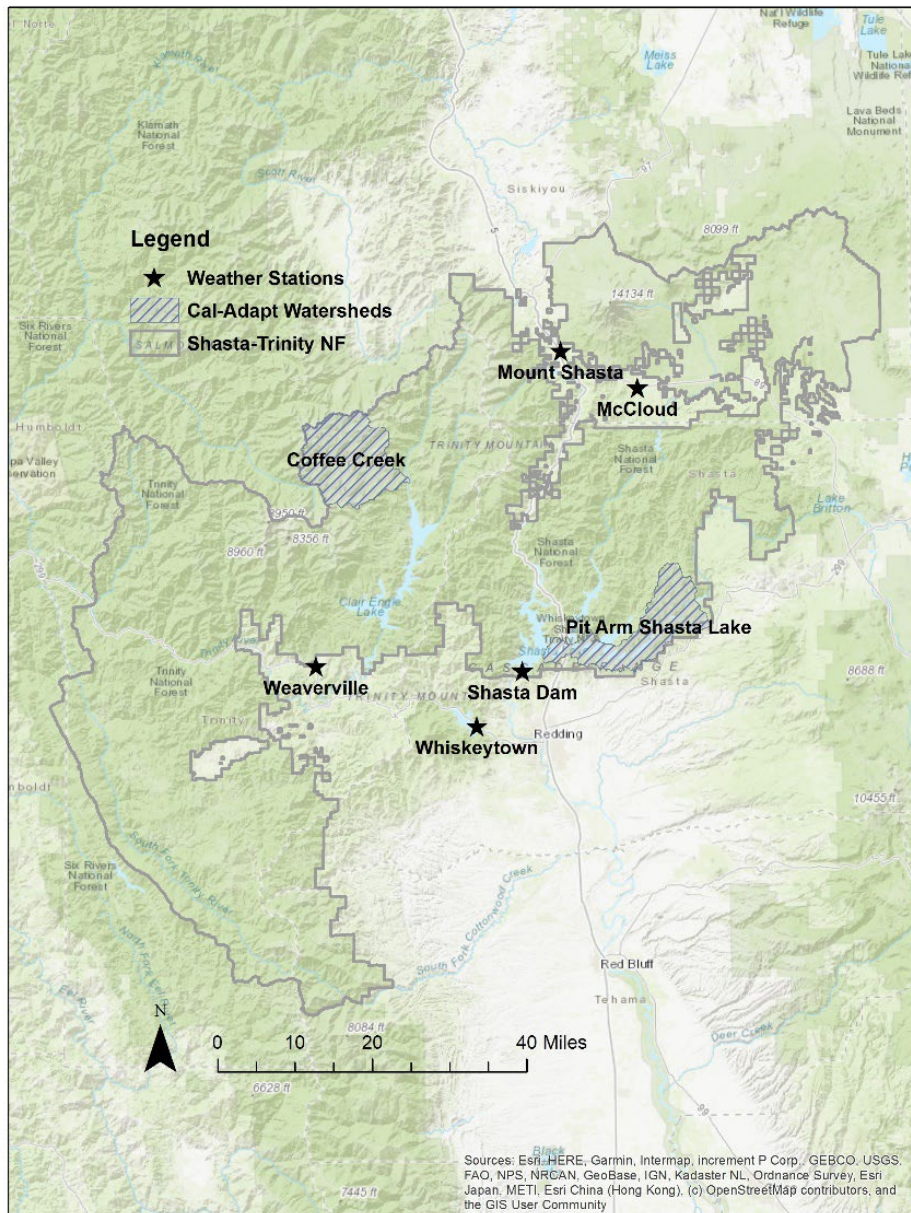
Figure 1. Locations of local weather stations and watersheds (see future climate projections) evaluated for this report. Weather station locations are indicated with a star while selected watersheds are indicated with a crosshatch.

Historical Climate Trends

Temperature

Based on TerraClimate, the average minimum temperature has increased by 1.93°F across the Shasta-Trinity National Forest since 1959. This trend is corroborated by statistically significant increases occurring across 4 out of the 5 weather stations (Mount Shasta being the exception with no significant change; Table

2, Figure 2). Increasing minimum temperatures typically affect the number of months that have temperatures below freezing, however the Weaverville station was the only one that showed a significant change with a little over a 1.5 month decrease in months with temperatures below freezing. Some of the weather stations rarely experienced freezing temperatures historically, so significant decreases in freezing months should not be expected for these stations. Two of the five weather stations (Shasta Dam and Whiskeytown) had a maximum of one month recorded for any given year where temperatures were below freezing since the beginning of their data sets. Significant increases in average mean annual temperature have been recorded at all the local weather stations (+1.66-2.76°F). Maximum temperature also showed a significant increase for 3 out of the 5 stations (+1.78-2.81°F).

The increases in annual temperature on the Shasta-Trinity National Forest are consistent with other climate analyses in California (e.g. Cordero et al. 2011), including California's North Coast region (e.g. Grantham 2018) and the Sierra Nevada (e.g. Gonzalez 2012), and at higher elevations in the western US (e.g. Diaz and Eischeid 2007). There has been an order of magnitude increase in warming between 1970-2006 compared to 1918-2006, indicating accelerated warming over a 37 year period in California (Cordero et al. 2011); warming has continued to increase since 2006. Rapacciuolo et al. (2014) report an average statewide temperature increase of 0.81°F between historic (1900-1939) and modern (1970-2009) times. The Northwestern California ecoregion, which includes the Shasta-Trinity National Forest, shows an increase in mean (+0.32°F) and minimum (+0.85°F) temperature and a decrease in maximum (-0.41°F) temperature over this same period (Rapacciuolo et al. 2014).

Table 2. Direction, magnitude, and statistical significance of temperature shifts on the Shasta-Trinity National Forest and relevant local weather stations.

	McCloud	Mount Shasta	Shasta Dam	Weaverville	Whiskeytown	Shasta-Trinity National Forest National Forest (TerraClimate)
	1911-2020	1988-2013	1944-2020	1913-2019	1961-2020	1959-2019
Mean Temperature (°F)	+2.45**	+1.66*	+1.99**	+2.42*	+2.76****	N/A
Min Temperature (°F)	+2.57**	ns	+1.20*	+3.87****	+2.98***	+1.93****
Max Temperature (°F)	ns	+1.78*	+2.44**	ns	+2.81**	ns
Freezing (mo/yr)	ns	ns	ns	-1.61***	ns	N/A

Numerical values are the estimated increase in temperature based on the total number of years in the period of record, calculated using Theil-Sen slope estimator. Directions and magnitudes of shifts are only shown for cases where rates of change are statistically greater or less than zero (p ≤0.05). Statistical significance indicated as follows: 'ns' not significant; '*' p ≤0.05; '**' p <0.01; '***' p <0.001; '****' p <0.0001. Near significant trends are noted in parenthesis. Data gaps of more than 3 consecutive years are noted.
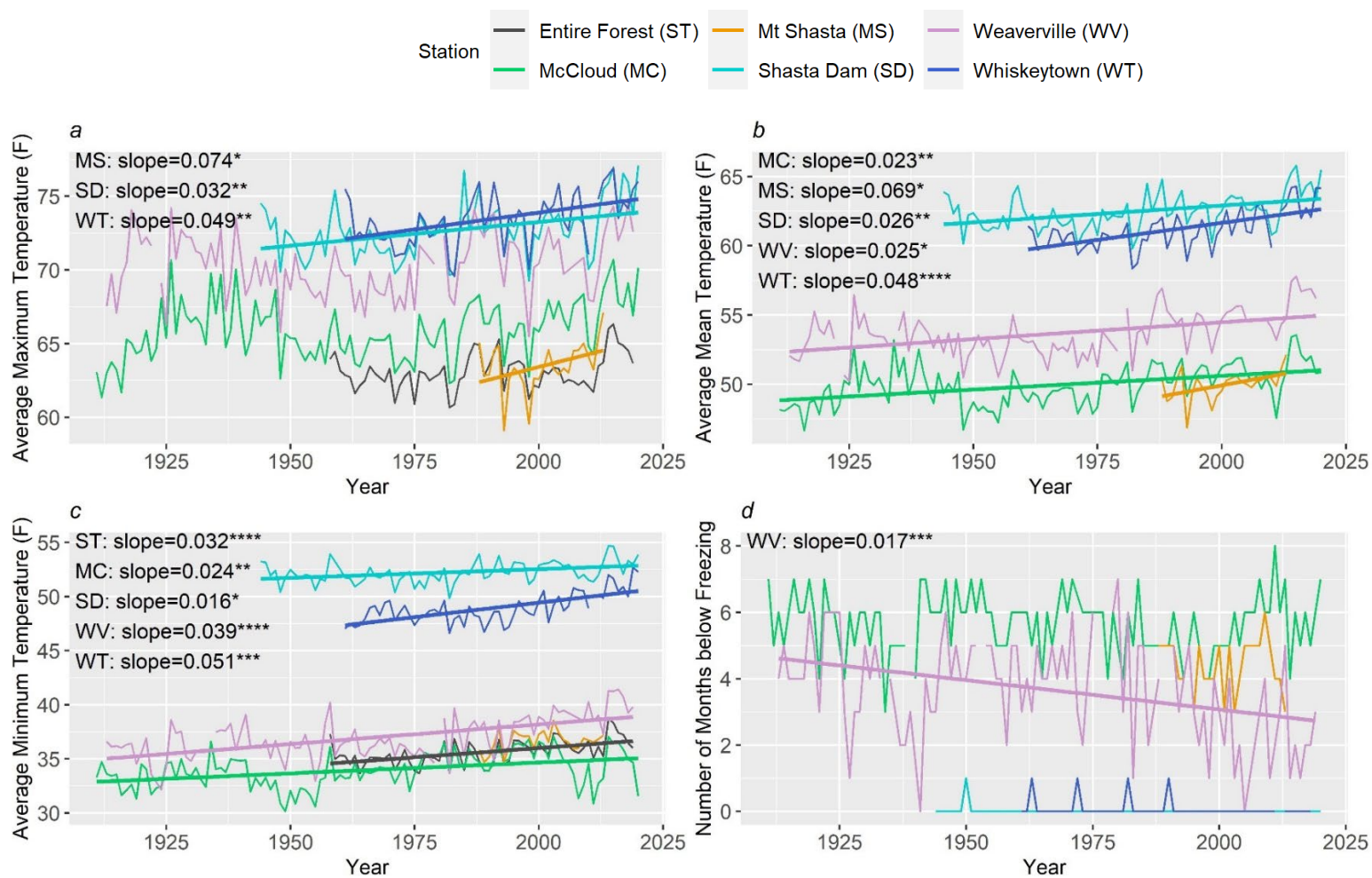
Figure 2. Historical temperature trends for the Shasta-Trinity National Forest and relevant local weather stations (identified in different colors): a) Average Maximum Temperature, b) Average Mean Temperature, c) Average Minimum Temperature, and d) Number of Months below Freezing (months where the average minimum temperature was <32^0F). Linear lines indicate a significant trend. For all significant trends the magnitude and direction of trend (slope) are presented, and the level of significance is indicated by number of asterisks (*$p<0.05$, **$p<0.01$, ***$p<0.001$, ****$p<0.0001$).

Precipitation

Historical trends in total precipitation were not significant at any of the weather stations on the Shasta Trinity National Forest (Figures 3-5). This is consistent with other research on precipitation trends in northern California and across the state more generally (He and Gautam 2016). Northern California receives more precipitation than any other part of the state (He and Gautam 2016) and, although this is not expected to change, we do expect to see increased variability in the timing of precipitation (Liu et al. 2018).

California has the highest interannual variability in precipitation in the continental United States (Gibson et al. 2020). The difference between a wet versus a dry year is often determined by a few storms, generally occurring in the form of atmospheric rivers[1] (Dettinger 2013, Ralph et al. 2018). Over the period of record, there has been high variability in annual precipitation across the Shasta-Trinity National Forest (Table 3, Figures 3 and 4) and there is a significant increase in variability over time at two of the stations: McCloud and Whiskeytown. This is consistent with other research that has observed increasing precipitation variability globally (Pendergrass et al. 2017) and in northern California specifically (He and Gautam 2016). Precipitation is expected to continue to increase in variability with climate warming in California and around most of the world (Pendergrass et al. 2017, Swain et al. 2018).

Like variability in total precipitation, there has been a high degree of variability in total snowfall across the Shasta-Trinity National Forest (Figure 5). Across the period of record there has been a large significant increase in total snowfall at the highest elevation weather station (+27.7 inches, Mount Shasta), yet TerraClimate shows a significant decrease of 4.52 inches of snow water equivalent (SWE) across the entire Shasta-Trinity National Forest (Table 3, Figure 5). Note that snowfall and SWE are not equivalent metrics: snowfall is inches of snow, while SWE is the amount of water in snow if the snow were to melt. Ten inches of snowfall generally translates to about one inch of SWE (Wang et al. 2017c), so the two metrics have different magnitudes but show similar trends. While trends in total snowfall were non-significant on the Shasta-Trinity National Forest declines in SWE have been documented across California, and more specifically, northern California (Mote et al. 2005).

The increase in snowfall at the Mount Shasta weather station may be due to limited data. The Mount Shasta weather station data record is the shortest of all the local weather stations (1988-2013), and missing data in 2010-2012 prevented these years from being included in the analysis, which may have impacted trends. Data after the 2013-2014 water year are incomplete and therefore unavailable for analysis here. This station has not seen any significant increases in minimum temperature or decreases in number of months with temperatures below freezing. Furthermore, other researchers have noted increases in glaciers and snowfall on Mt. Shasta as well as some other high-elevation areas of California (Howat and Tulaczyk 2005, Howat et al. 2007). In a California-wide analysis, Howat and Tulaczyk (2005) found that sites below about 7500 ft (2300 m) in elevation showed an average 13% decline in SWE, while sites above this line showed an average 12% increase in SWE. This can be attributed to increased winter precipitation due to orographic lifting of warm, moist air resulting in increased snowfall at high elevations

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[1] Atmospheric rivers are long, narrow regions in the atmosphere that transport water vapor outside of the tropics and then release that water vapor in the form of rain or snow when they make landfall.

(Howat and Tulaczyk 2005). At present, this effect outweighs the impact of increasing temperature at high elevations, but this is likely to change in the future. Mt Shasta is projected to lose nearly all its glaciers by the end of the century if warming trends continue, despite current increases in glacier sizes (Howat et al. 2007). The Mt. Shasta weather station may or may not be impacted by this effect. While the peak of Mt. Shasta reaches 14,179 ft, the weather station is located closer to the town of Mt. Shasta and is at an elevation of only 3590 ft, with no significant increases in total precipitation over the period of record.

Table 3. Direction, magnitude, and statistical significance of precipitation shifts on the Shasta-Trinity National Forest and relevant local weather stations.

	McCloud	Mount Shasta	Shasta Dam	Weaverville	Whiskeytown	Shasta-Trinity National Forest (TerraClimate)
	1910-2003[1]	1988-2013	1943-2018	1916-2018[3]	1960-2017	1959-2019
Total Precipitation (in.)	ns	ns	ns	ns	ns	ns
Coefficient of variation	11.8*	ns	ns	ns	22.8*	ns
	1927-2003[2]	1988-2013	1944-2018	1945-2017[4]	1960-2017	1959-2019
Snowfall (in.)	ns	+27.7***	0*	ns	ns	N/A
Snow Water Equivalent (in.)	N/A	N/A	N/A	N/A	N/A	-4.52*

[1]Missing: 1911-1923, 1937-1943; [2]Missing: 1936-1943; [3]Missing: 1917-1930, 1939-1942, 1979-1982, 1984-1989, 1991-1995; [4]Missing: 1974-1977, 1982-1991, 2010-2015. Numerical values are the estimated increase in precipitation based on the total number of years in the period of record, calculated using Theil-Sen slope estimator. Directions and magnitudes of shifts are only shown for cases where rates of change are statistically greater or less than zero (p ≤0.05). Statistical significance indicated as follows: 'ns' not significant; '*' p ≤0.05; '**' p <0.01; '***' p <0.001. Near significant trends are noted in parenthesis. Results for precipitation are organized by water-year. Data gaps of more than 3 consecutive years are noted.

Figure 3. Five-year coefficient of variation in precipitation for local Shasta-Trinity National Forest weather stations (identified in different colors), and for Shasta-Trinity National Forest overall (shown in black). Linear trend lines are shown for weather stations that have had significant changes in coefficient of variation over time. For all significant trends the magnitude and direction of trend (slope) are presented, and the level of significance is indicated by number of asterisks (*p<0.05, **p<0.01, ***p<0.001, ****p<0.0001).

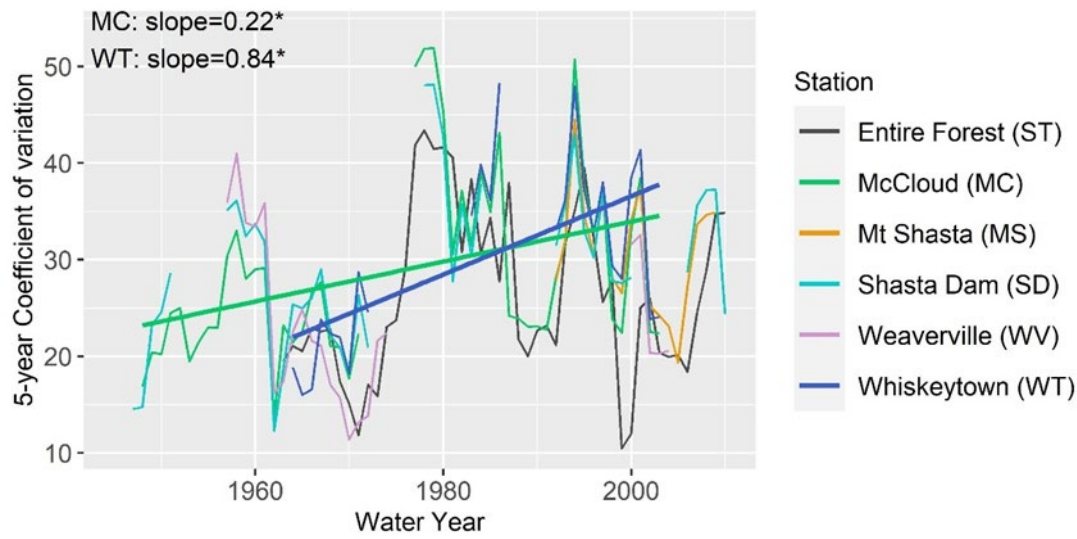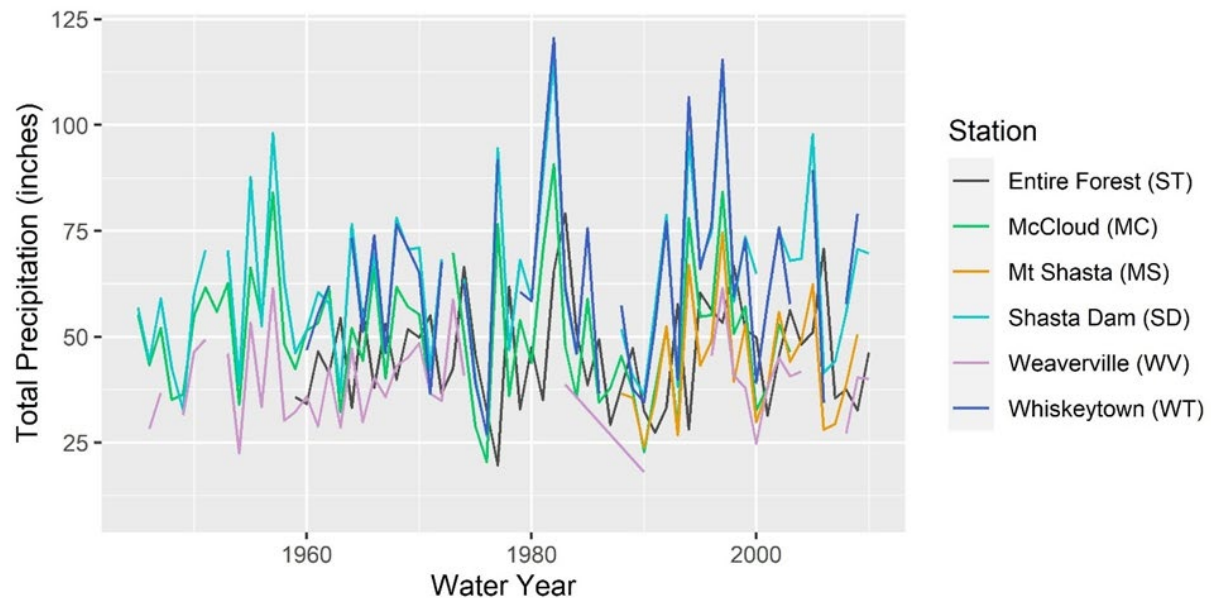**Figure 4.** Total precipitation for local Shasta-Trinity National Forest weather stations (identified in different colors), and for Shasta-Trinity National Forest overall (shown in black). No trends were statistically significant.
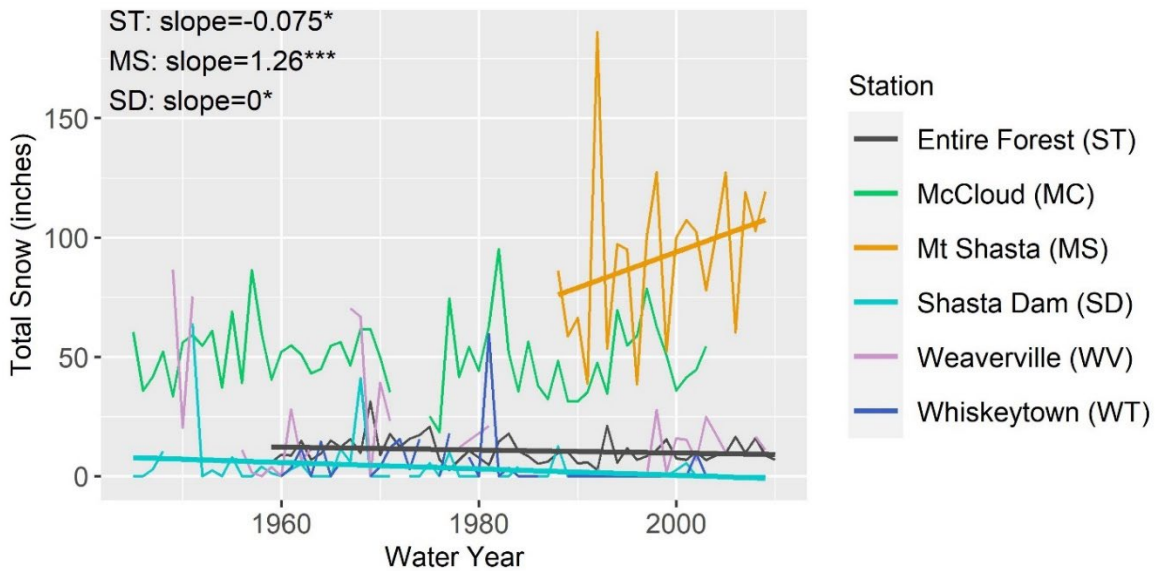
Figure 5. Total snowfall for local Shasta-Trinity National Forest weather stations (identified in different colors), and for Shasta-Trinity National Forest overall (shown in black). Linear lines indicate a significant trend. For all significant trends the magnitude and direction of trend (slope) are presented, and the level of significance is indicated by number of asterisks (*p<0.05, **p<0.01, ***p<0.001, ****p<0.0001)[2]. Note that data for the Shasta-Trinity National Forest are snow water equivalent (inches), while data for the individual weather stations are total snow (inches).

Hydrology

Changing hydrology in California is influencing vegetation, wildfire, wildlife, and public health. Across the western United States, widespread changes in surface hydrology have been observed since the mid-1900s. These shifts include: decreased snowpack (particularly at low elevation sites; Mote et al. 2005, Barnett et al. 2008, Grundstein and Mote 2010); a decrease in the annual precipitation falling as snow (Knowles et al. 2006, Klos et al. 2014, Knowles 2015); decreased snow depth, particularly at low elevation sites (Mote et al. 2005, Barnett et al. 2008, Grundstein and Mote 2010); earlier snow melt and spring runoff (Stewart et al. 2005, Hamlet et al. 2007, Maurer 2007, Barnett et al. 2008); decline in total runoff occurring in the spring (Moser et al. 2009); rising river temperatures (Kaushal et al. 2010), increased variability in streamflow (Pagano and Garen 2005); and increased evapotranspiration from longer growing seasons that has increased soil water deficits since the 1970s (Abatzoglou et al. 2014). Snowmelt in California contributes a huge proportion of water to agricultural and public supplies and is extremely vulnerable to climate-related hydrological changes. Across California, springtime SWE has decreased by 50-75% between 1950 and 1997 (Mote et al. 2005). The average spatial extent of snow above 3000 feet in elevation on April 1st declined from 60% to 50% between 1951-1980 and 1981-2010 for California's

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[2] The Mann-Kendall test is based on the signs of the differences in values whereas the Sen's slope estimate is the median of all the two-point slopes. A Sen slope of 0 can be significant if more than half of the two-point slopes are zero.

North Coast, with the Klamath-Siskiyou Mountains exhibiting the greatest losses (Micheli et al. 2018). Across California, precipitation falling as snow has declined and was more variable over the timeframe between 1916 and 2003, and even more markedly so when examining only the more recent years after 1960 (Safeeq et al. 2016). Underlying these general trends, the range of hydrologic responses to climate change is influenced by geography and elevation.

Warming temperatures and rain-on-snow events influence snowmelt timing, which in turn, influences annual hydrology patterns and how long water is available to plants and wildlife throughout the dry season. The western US has experienced widespread changes in surface hydrology since the mid-1900s, including earlier snowmelt and spring runoff (by 0.3 to 1.7 days per decade; Stewart et al. 2005, Hamlet et al. 2007, Maurer 2007, Barnett et al. 2008). Analyses of hydrometeorological data from the lower Klamath Basin show a decrease in the percentage of precipitation falling as snow and accelerated snowpack melt, resulting in earlier peak runoff and lower base flows (Hamlet et al. 2005, Mote et al. 2005, Regonda et al. 2005, Stewart et al. 2005, Mote 2006, Van Kirk and Naman 2008). Long term shifts in the timing of streamflow have been observed for snowmelt dominated basins since the late 1940's, resulting from early snow melt (Mote 2003, Hamlet et al. 2005, Mote et al. 2005, Regonda et al. 2005, Stewart et al. 2005). Moser et al. (2009) found that over the past 100 years, the fraction of annual runoff that occurs during April–July has decreased by 23% in the Sacramento River basin and by 19% in the San Joaquin River basin in California. During this same time snowpack accumulation has decreased (Mote et al. 2005). Knowles et al. (2006) found that shifts in precipitation from snow to rain have occurred since the middle of the last century and this shift has been linked to atmospheric rivers (Hatchett et al. 2017). While atmospheric rivers have been linked to the decline in snow, they are also important in California as they have also been noted as ending 33-44% of all persistent droughts (Dettinger 2013). Trends in April 1 snow water equivalent (SWE) appear to be driven by temperature, which is mostly a function of elevation and latitude (Knowles and Cayan 2004, Mote 2006), and secondarily by precipitation (Hamlet et al. 2005, Mote et al. 2005, Stewart et al. 2005). Additionally, fog frequency along the coast of northern California declined by 33 percent during the 20th century (Johnstone and Dawson 2010). Fog provides an important source of moisture for coastal forests, and future drought stress is likely to increase with declining fog levels (Johnstone and Dawson 2010). Summertime coastal low clouds have also declined by around 5% between 1950-1959 and 2000-2009, which may lead to further temperature increases and drought stress (Schwartz et al. 2014).

Earlier snowmelt has resulted in earlier peak runoff and long-term shifts in the timing of streamflow (Mote 2003, Hamlet et al. 2005, Mote et al. 2005, Regonda et al. 2005, Stewart et al. 2005, Mote 2006, Van Kirk and Naman 2008). Snowpack has declined across the Klamath Basin since the 1950s, leading to lower annual flows in all stream types (Mayer and Naman 2009). In the Upper Basin of the Klamath River, reservoirs are relatively shallow and provide little carry-over storage from year to year, so water levels are sensitive to current year precipitation and snowmelt. In the past, low flows and warm temperatures in the Klamath have led to deaths of many Chinook salmon, and heightened conflict over agricultural water use (Dettinger et al. 2015). Earlier snowmelt results in less water availability to forest vegetation (Tague and Peng 2013, Blankinship et al. 2014) and causes higher groundwater recharge and reduced total streamflow (Barnhart et al. 2016). Changing snowmelt timing can have perilous human health and safety repercussions, such as the disastrous Oroville Dam spillway overflow in 2017, which

resulted in 180,000 people evacuating, after a winter in which early season runoff increased by 30% and the April 1 SWE decreased by 20% due to early melt (Huang et al. 2018).

Stream gauge data and climate stations in northwestern California show that summer low flows have decreased and summer stream temperatures have increased in many of northern California's coastal rivers over the last century (Madej 2011, Bauer et al. 2015). In an analysis of gauge data from 21 river gaging stations in an area that covers portions of the Mendocino, Shasta-Trinity, Klamath, and Six Rivers National Forests, 10 of the gauges showed an overall decrease in seven-day low flow (Madej 2011, Bauer et al. 2015). Similarly, Asarian and Walker (2016) observed significant declines in the magnitude of 7-day, 30-day, and 90-day low flows for about half of the 41 flow monitoring sites across northern California and southern Oregon. They also found declines in overall summer streamflow over the last half-century, with the most consistent declines evident between August and November. Stream gauge data from the Columbia River Basin in the Pacific Northwest showed a 16% decline in spring flow volume, a 5.7-day advancement of spring flow onset, and a 5-38% decline in low flow volume over the last century (Dittmer 2013).

In addition to temporal hydrological shifts, California has also exhibited one of the greatest increases in variability in streamflow in the western U.S. since the 1980s (Pagano and Garen 2005). Hydrologic extremes, droughts, and floods are predicted to intensify under climate change (Pachauri et al. 2014) and these trends are already apparent in the western US (Hayhoe et al. 2004, Kadir et al. 2013). This increased variability in high and low flows, coupled with high year-to-year persistence (i.e., the probability that a wet year is followed by another wet year or a dry year by a dry year), has resulted in extended and extreme dry and wet spells that are particularly challenging for management of urban infrastructure and other services (Pagano and Garen 2005). The timing and duration of significant pulses in discharge are particularly important in river ecosystems such as the Eel River Basin of northern California, where native biota are adapted to Mediterranean seasonality of flows (Kupferberg et al. 2012, Power et al. 2015).

Drought

The recent California drought (2012-2016) was arguably the most severe of the last millennium (Griffin and Anchukaitis 2014, Mann and Gleick 2015, Lund et al. 2018, Dong et al. 2019). The drought occurred due to low precipitation combined with record high temperatures (Griffin and Anchukaitis 2014). This resulted in 2015 April SWE that was so low that Belmecheri et al. (2016) estimated that this was a one-in-3100 year event. Although northern California was less impacted by the 2012-2016 drought than other parts of the state, from 2012-2015 the northern coastal region received only 77% of the precipitation it would normally receive (He et al. 2017). This had impacts on streamflow in critical fish habitat, resulting in multi-month stretches of dry streambeds and only 1-5% of the summer flow that was seen in wetter years (Deitch et al. 2017, Deitch et al. 2018). In winter 2016-2017, California experienced a dramatic shift towards extreme precipitation events and severe flooding (Wang et al. 2017a, Wang et al. 2017b, Swain et al. 2018). Even after the drought ended, it took two years for streamflow to recover in north-central coastal California (Deitch et al. 2017). Moisture stress associated with drought and high temperatures during the early 21st century is evident across many vegetation types (Asner et al. 2016, Mildrexler et al. 2016), and research in the Klamath Mountains indicates that tree mortality in 2013-2014 was higher than in any other year from 1986-2012 (Bost 2018).

Moderate to exceptional drought is currently being reported for the entire state of California, with severe to extreme drought across northwestern California as of July 2022 (National Drought Mitigation Center 2022). This drought is anticipated to persist over at least the near term (Climate Prediction Center 2022).

Historical Fire Trends and Fire-Climate Interactions

Climate is a primary driver of fire activity (Westerling et al. 2003, Littell et al. 2009, Krawchuk and Moritz 2011). Although the relationship between climate and fire has been moderated by human activities such as fire suppression, logging, grazing, and development (Parks et al. 2016, Syphard et al. 2017), paleoecological and other studies have shown that over long timeframes, changes in fire activity can primarily be explained by large-scale changes in climate (Kitzberger et al. 2007, Marlon et al. 2008, Power et al. 2008, Whitlock et al. 2008). This pattern holds true for the western US in the 20th century, where climate has been a strong driver of fire size, frequency, and severity (Westerling and Bryant 2006, Littell et al. 2009, Dillon et al. 2011, Abatzoglou and Williams 2016, Westerling 2016).

The influences of climate on fire activity differ regionally, act at various temporal scales, and include both direct and indirect effects. Climate influences wildfire primarily by affecting fuel abundance in fuel-limited environments, and by influencing fuel moisture and fire weather conditions in productive areas (Krawchuk and Moritz 2011, Batllori et al. 2013). Direct effects of climate include droughts, storm events, fire season length and effects on fuel availability and flammability (Krawchuk and Moritz 2011, Kitzberger et al. 2017). Indirect effects include shifts in species composition and productivity, mortality rates, and post-fire germination and establishment (Davis et al. 2018, Coop et al. 2020). These factors are not mutually exclusive and may have synergistic effects.

Wildfire activity has dramatically increased across the western United States (US) over the past four decades, including area burned, fire frequency, the total number of fires and the number of large fires, and fire season length (Westerling and Bryant 2006, Littell et al. 2009, Dennison et al. 2014, Lannom et al. 2014, Abatzoglou and Williams 2016, Mann et al. 2016, Westerling 2016). In California, acres burned statewide have increased since 1950, and most of the largest wildfires ever recorded have occurred in the past two decades (Office of Environmental Health Hazard Assessment 2018). Northern California forests have seen substantially increased wildfire activity, with most wildfires occurring in years with early springs (Westerling et al. 2006). This increase is likely attributable to both climate and land-use effects. Large increases in moisture deficits in northern California forests were strongly associated with advances in the timing of spring (Westerling et al. 2006, Prein et al. 2022), but this area also includes substantial forested area where forest densification after fire exclusion and timber harvesting have led to increased fuel loads and fire risks (Frost and Sweeney 2000, Bohlman et al. 2021).

Much of northern California has missed multiple fire cycles owing to fire suppression, with low- and mid-elevation vegetation types such as oak woodlands, yellow pine, and mixed-conifer forests missing the most fire cycles (Safford and Van de Water 2014, Bohlman et al. 2021). More than 68 percent of Forest Service lands in North Zone[3] are burning either less frequently or much less frequently than under the

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[3] Klamath, Lassen, Mendocino, Modoc, Shasta-Trinity, and Six Rivers National Forests

pre-Euro-American settlement fire regime, as compared with 82 percent in the Central Zone[4], 45 percent in the Southern Sierra Zone[5], and 29 percent in the South Zone[6] (Safford and Van de Water 2014).

Miller et al. (2012) found no temporal trend in the annual proportion of fire area burning at high severity within fires >400 ha (1000 ac) on the four National Forests of northwestern California during the period 1987-2008. However, mean and maximum fire size and total annual area burned all increased over the period from 1910 to 2008 and regional fire rotation fell to 95 years by 2008, after reaching a high of 974 years in 1984. Miller et al. (2012) also found that years with larger fires and greatest area burned were produced by region-wide lightning events and characterized by less winter and spring precipitation than in years dominated by smaller human ignited fires, but that the percentage of high-severity fire was generally less in region-wide lightning events often due to the moderating effects of smoke inversions (Estes et al. 2017). Although remotely sensed fire severity data have only been available since 1984, fire severity has been increasing in many western US ecosystems over this short time frame (Miller et al. 2009, Dillon et al. 2011, Miller and Safford 2012, Dennison et al. 2014, Singleton et al. 2019). From 1984-2015, yellow pine and mixed-conifer forests across California have seen increasingly large proportions of high-severity fire and decreases in unburned or low-severity patches (Steel et al. 2018). Areas that burn at high severity are more likely to re-burn at high severity, leading to a feedback loop of increasingly large high-severity patches (McCord et al. 2020, Taylor et al. 2021).

Temperature, precipitation, and snow cover

Numerous studies suggest that temperature is the most important factor driving fire activity (Flannigan et al. 2009). In the western US, fire activity is strongly correlated with dry, warm conditions during the fire season (Littell et al. 2009, Spracklen et al. 2009, Westerling 2016). Although average annual precipitation in California has not changed over the past century (Office of Environmental Health Hazard Assessment 2018), increases in temperature without concurrent increases in precipitation have increased climatic water deficit across the region (Miller and Urban 1999). Increases in area burned in recent decades have been associated with warmer temperatures resulting in increased climatic water deficit (Dennison et al. 2014, Lannom et al. 2014, Westerling 2016). Crockett and Westerling (2018) found that both fire size and severity were greater during droughts, and in California, the area burned by wildfires has increased in parallel with increasing air temperatures (Office of Environmental Health Hazard Assessment 2018). Littell et al. (2009) found that in the Sierra Ecoprovince (which includes the Klamath Mountains and southern Cascades), high temperatures, low precipitation, and drought immediately prior to and during the fire season most strongly affected fire activity.

Increased temperatures over the past century have also affected fire behavior by causing earlier spring snowmelt and by increasing the length of the fire season (Westerling et al. 2006, Westerling 2016). Westerling (2016) showed that the largest fires in the western US occurred in years with warm springs and early spring snowmelt dates, and that fire seasons in 2003–2012 averaged more than 84 days longer than in 1973–1982. Years with the earliest spring snowmelt accounted for more than 70% of the area burned in large forest wildfires between 1970–2012. Abatzoglou and Williams (2016) estimate that

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[4] Eldorado, Plumas, Stanislaus, and Tahoe National Forests and Lake Tahoe Basin Management Unit

[5] Inyo, Sequoia, Sierra, and Stanislaus National Forests

[6] Angeles, Cleveland, Los Padres, and San Bernadino National Forests

anthropogenic climate change resulted in an average of 17 additional days per year of high fire potential in the period between 2000–2015 compared with 1984-1999.

Precipitation patterns are known to influence fire activity by affecting fuel production. In grass and shrubland systems, precipitation prior to the fire season can significantly increase the amount and continuity of fine fuels (Westerling and Bryant 2008, Littell et al. 2009, Spracklen et al. 2009). For example, Keeley and Syphard (2015) found that in non-forested ecosystems of the foothills and valleys of California, area burned is influenced primarily by higher rainfall prior to the fire season that results in increased herbaceous fuel volume. However, the effect of antecedent precipitation is apparent in forested systems as well. Large fires may be most likely in dry and hot years (Taylor et al. 2008), and when a wet year occurred three years previously (Fry and Stephens 2006). Littell et al. (2009) found that the model that best explained the increase in area burned in the Sierra Ecoprovince between 1977 and 2003 included precipitation in the winter prior to the fire. California experiences unusually large variations in annual precipitation relative to the rest of the US, with only a small number of wet days (5-15) per year needed to accumulate annual precipitation totals (Dettinger 2011). Variability in annual precipitation in California has increased since the early 1980s, and this variability can further promote fire activity when very wet years promote fuel production, leading to large areas burned when subsequent years are dry (He and Gautam 2016).

Lightning activity is positively correlated with surface temperatures on short time scales. Significant declines in snow cover and spring snowpack over the past century exponentially increased the number of lightning-ignited fires in the Sierra Ecoprovince. High levels of snowpack keep surface temperatures low, decreasing the convective forces necessary for lightning (Lutz et al. 2009b). However, Chen and Jin (2022) found that higher SWE increases available water for spring vegetation growth in the Sierra Nevada mountains and northern interior forests of California, which lead to increased fine fuels in dry and hot summers and likely enhance lightning ignitions.

Fuel aridity effects

One of the primary ways that increased warming promotes fire activity is by drying fuels (Littell et al. 2009). Abatzoglou and Williams (2016) found that anthropogenic increases in temperature and moisture deficit significantly enhanced fuel aridity across western US forests, resulting in larger fires (Figure 6). They estimate that climate change (excluding change attributed to natural phenomena) caused 75% more forested area to experience high fire-season fuel aridity in 2000–2015 compared with 1984-1999. As a result, human-caused climate change contributed to an additional 10.4 million acres of forest burned in the western US between 1984 and 2015, nearly doubling the amount of forest fire that would have been expected without anthropogenic warming under the past century of active fire management. Williams et al. (2019) found that the positive correlation between fire activity and fuel aridity was stronger in both the Sierra Nevada and the North Coast than in most other areas of California.
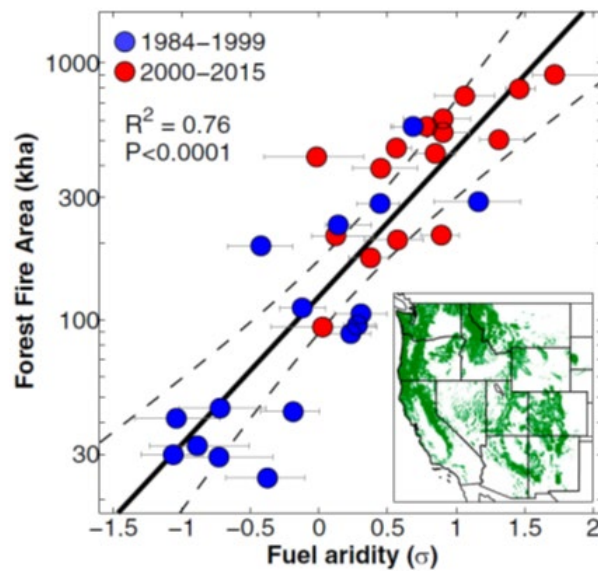
Figure 6. Annual western US forest fire area versus fuel aridity from 1984-2015. From (Abatzoglou and Williams 2016).

Historical Vegetation Trends

While long-term shifts in vegetation distribution, composition, and structure are difficult to observe, short-term shifts in response to drought and climate variability can offer insight into the trends we are likely to see under warmer and drier climates. Vegetation in California has changed over the last century due in part to direct changes in temperature and precipitation (Cordero et al. 2011, Rapacciuolo et al. 2014, Hatchett et al. 2017, Gibson et al. 2020) and indirect climate effects on disturbances such as wildfire and drought (Hurteau et al. 2019). This, in conjunction with past management (e.g., fire exclusion), has led to alterations in vegetation components. These changes are not spatially consistent, rather they vary by latitude, elevation, and local management history, making some community types more vulnerable to climate exposure both currently and in the future (Thorne et al. 2017).

Distribution of vegetation

Most of the changes observed in vegetation over the last century can be linked to coupled effects of land-use decisions and climate change. For example, many forests were harvested using even-aged systems early in the 1900s followed by a diverse group of silvicultural operations (Laudenslayer and Darr 1990) which altered composition and structure. In addition, fire suppression has been practiced as a federal policy since 1935 and has resulted in increased tree densities and a reduction in shade intolerant species (Parsons and Debenedetti 1979, North et al. 2007). Skinner (1995) found that forest openings decreased and distances between openings increased from 1944 to 1985 in portions of the Dillon, Clear, and Swillup Creek watersheds near Happy Camp. The ecological significance of changes associated with fire suppression is generally more important in drier, historically pine-dominated forests than in moister, fir-dominated forests due to their different historical fire regimes (Bohlman et al. 2021, Coppoletta et al.

2021). Working at Whiskeytown National Recreation Area, Leonzo and Keyes (2010) documented major changes over the last half century in the structure and composition of "relict" old-growth ponderosa pine stands, with young individuals of shade tolerant species like Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), and tanoak (*Notholithocarpus densiflorus*) comprising 10 times higher stem densities than the once dominant pine.

Structure and composition of forests

Modern tree density is significantly higher compared to conditions a century ago (Dolanc et al. 2014a, Dolanc et al. 2014b, McIntyre et al. 2015). This increase is skewed towards smaller trees (Dolanc et al. 2014b) as recruitment and growth of shade-tolerant species has increased, shifting mixed conifer stands to denser fir- and incense cedar (*Calocedrus decurrens*)-dominated stands (Levine et al. 2016, Moran et al. 2019). These changes have made forests more susceptible to water-stress related issues attributed to climate change. Although overall tree density is up, the density of large trees has decreased over the last century, largely driven by past logging practices and climate- and stand density-driven water stress (Dolanc et al. 2014b, Easterday et al. 2018). Van Mantgem et al. (2009) documented widespread increases in tree mortality in old-growth forests across the west, including northern California, although their plots had not experienced increases in density or basal area during the 15–40-year period between first and last census. The highest mortality rates were documented in the Sierra Nevada, and in middle elevation forests (3300-6700 feet). Higher elevation forests (>6700 feet) showed the lowest mortality rates. Van Mantgem et al. (2009) ascribed the mortality patterns they analyzed to regional climate warming and associated drought stress.

Evidence suggests that old-growth forests can be susceptible to a wide range of stressors, including the disruption of historical disturbance regimes such as fire (Skinner et al. 2006), invasive species and pathogens (McDonald and Hoff 2001, Rizzo and Garbelotto 2003), and increasing temperatures (van Mantgem et al. 2009, Allen et al. 2010, Peng et al. 2011, Williams et al. 2013). Work by van Mantgem and Sarr (2015) in diverse old-growth forests across a broad range of climates in the Klamath region further demonstrates the high correlation between forest structure and diversity with climate, as well as the complexity inherent in predicting future forest conditions in this region.

Effects of severe drought on vegetation

The 2012–2016 California drought may have been the most extreme drought event in the last 1,200 years (Griffin and Anchukaitis 2014, Robeson 2015). The drought's primary outcome was the initiation of a severe tree mortality event in forests primarily in the Sierra Nevada (Paz-Kagan et al. 2017, Preisler et al. 2017, Young et al. 2017, Fettig et al. 2019a). During this drought period, tree mortality increased to an estimated 129 million trees dying across the state (Young et al. 2017, Young et al. 2019), going from a median of <10 dead trees per square mile in 2009-2014, to a median of c. 130 dead trees per square mile in 2015 (Young et al. 2017). The primary mortality agents were expanded populations of bark beetles (Coleoptera: Curculionidae, Scolytinae) occurring primarily in large areas of water-stressed forest (Fettig 2016, Fettig et al. 2019a). The western pine beetle (*Dendroctonus brevicomis*), which attacks ponderosa pine (*Pinus ponderosa*) was the primary driver of landscape-level mortality. However, the mountain pine beetle (*Dendroctonus ponderosae*), which attacks a number of pines (*Pinus* spp.), and the fir engraver beetle (*Scolytus ventralis*) also contributed to tree mortality (Fettig 2016).

Tree mortality patterns as a result varied over broad moisture and precipitation gradients, especially elevation and latitude with the greatest levels of tree mortality occurring in the low to mid elevation ponderosa pine and dry mixed conifer forests at more southern latitudes (centered on the Sierra and Sequoia National Forests) (Brodrick and Asner 2017, Paz-Kagan et al. 2017, Restaino et al. 2019). These areas coincided with greater moisture stress and climatic water deficit (Asner et al. 2016). Some upper montane forests (e.g., red fir [*Abies magnifica*]) also exhibited widespread mortality in the region. Tree mortality tended to increase with topographic dryness, such as on southwest-facing slopes, in shallower soils, and at greater distances from perennial water sources (Paz-Kagan et al. 2017). Tree mortality levels in ponderosa pine and sugar pine were most pronounced in the middle of the drought (2013-2015) and impacts to white fir and incense cedar were more prominent during late drought conditions (2016-2017) (Preisler et al. 2017, Pile et al. 2019).

Forest structure, composition, and function did not change as substantially in northwestern California as it did in the Sierra Nevada in response to the 2012-2016 drought event, but trends observed in the Sierra are helpful for understanding how to prevent or mitigate large-scale mortality events in the future. Tree species that experienced the highest mortality levels tended to be shade-intolerant pines in montane forests of the southern Sierra Nevada (i.e., ponderosa pine and sugar pine [*Pinus lambertiana*]). Increased mortality was observed in stands with more and/or larger trees, especially in dry sites, suggesting that water availability and competition for water play important roles in shaping susceptibility to bark beetles and ultimately tree mortality (Young et al. 2017). Except in the smallest size classes (<5 inches dbh), nearly all dead and dying ponderosa and sugar pines exhibited recent attack by bark beetles (Fettig et al. 2019a).

Shade-tolerant conifers in the montane and upper montane zones such as white fir, red fir, and incense cedar had the next highest mortality levels, followed by – in descending order – singleleaf pinyon pine (*Pinus monophylla*), gray pine (*Pinus sabiniana* - foothill zone), Jeffrey pine (*Pinus jeffreyi*), and lodgepole pine (*Pinus contorta* - upper montane zone). Relatively lower levels of mortality occurred in oaks (*Quercus* spp. with some localized areas of higher blue oak mortality in the foothill zone), and the lowest mortality levels were observed in giant sequoia (*Sequoiadendron giganteum*) and subalpine conifers such as whitebark pine (*Pinus albicaulis*) and foxtail pine (*Pinus balfouriana*) (Bentz et al. 2010, Paz-Kagan et al. 2017). This selective mortality resulted in reductions in stand density and basal area of live trees and may drive longer-term shifts in community composition along the elevational gradient, such as increased density of oaks (Fettig et al. 2019a, Young et al. 2019). The interactive effects of climate warming were also evident in tree species exhibiting increased crown loss and tree mortality rates prior to or at the onset of the 2012-2016 drought, such as red fir, whitebark pine, and giant sequoia (Mortenson et al. 2015, Stephenson et al. 2018, Millar and Delany 2019).

Historical Wildlife Trends

Climate change is impacting terrestrial wildlife species in a variety of ways across northwestern California, both directly and indirectly. Due to varying life history traits, physiological characteristics, and habitat requirements, species show differing degrees of vulnerability and adaptability to changes in climate.

Direct impacts

Physiological effects and range shifts

Changes in climate can have direct physiological effects on species that may result in reductions in reproduction and survival. Responses to direct impacts may result in population decline or changes to a species' range. Species range shifts are expected to occur where climate change alters rates of survival and reproduction across a species' distribution. As conditions deteriorate along one edge of the historical distribution (e.g., at lower latitudes and/or elevations) and improve along the other (e.g., higher latitudes and/or elevations), range contraction and/or expansion may occur. Species with a high degree of habitat specialization (like old forest specialists) and a narrower natural thermal range are more sensitive to climate change than other species and may be especially prone to move as climates warm (Jiguet et al. 2006, Gardali et al. 2012).

Direct effects of climate warming are predicted to force species upslope and northward, while indirect effects leave a more complex signature. Studies in other parts of California suggest that wildlife are already moving in response to changing climates to maintain environmental associations to which they are adapted (small mammals: Moritz et al. 2008, Rubidge et al. 2011); (butterflies: Forister et al. 2010); (birds: Tingley et al. 2009).

Individual bird species vary in their responses to climate change, with some populations increasing and others decreasing (Furnas 2020). Climate change is likely to create "winners and losers" among wildlife species, potentially leading to declines in species richness and diversity. Winners may include the northern goshawk, which has exhibited positive responses to higher-than-average late-winter and early-spring temperatures (Keane et al. 2006). Northern goshawk reproduction may be greatest in years with mild late winters and early springs with higher temperatures and low total precipitation. Similar trends appear in many other bird species, showing increased productivity in warmer, drier springs (Roberts et al. 2019, Saracco et al. 2019). Losers may include species like neotropical migrant birds, some of which have already begun to show range shifts in northern California, with fewer neotropical migrants below 1515m in elevation, and more above 1515m elevation over the course of 2002-2016 (Furnas 2020). These upslope shifts mean that there is less habitat available for the birds, as only 38% of forest habitat occurs above 1515m elevation (although this may change over time as tree species distributions also begin to shift upslope).

Old growth-dependent species, such as the spotted owl, may be more vulnerable to climate change. Declines in survival and recruitment may be linked to changes in prey populations rather than direct physiological impacts. Historically, NSO have been negatively impacted by cold and wet conditions during the winter and during the spring nesting season (Franklin et al. 2000, Duggar et al. 2005, Glenn et al. 2011, Olson et al. 2004). However, warmer winters are not necessarily better for NSO. While the worst years for spotted owl reproduction are preceded by cold and wet winters, the best years are preceded by cold and dry winters (Duggar et al. 2016). Increases in winter storms (Glenn et al. 2011) or the number of hot summer days (Glenn et al. 2010) may also have negative impacts on NSO populations. If future conditions involve higher summer temperatures, more extreme precipitation events, and wetter winters, the overall impact on NSO is likely to be negative (Glenn et al. 2010).

One of the more direct drivers of climate vulnerability is the fact that some species experience heat stress at lower temperatures than others. American pikas, for example, are an alpine species that can experience heat-related mortality at temperatures of 77.9-84.9˚F (25.5-29.4˚C), and warming temperatures have already been a key driver of distribution changes for this species (Mathewson et al. 2017). Among 20 California mammals ranked in terms of climate vulnerability, the American pika is among the most vulnerable. Of the mammals ranked most vulnerable, the American pika is the only one to occur in northern California (Stewart et al. 2016).

Many mammal species have shown greater vulnerability to warming trends than birds. Studies of habitat use by Pacific fisher suggest that fishers select sites with reduced heat loads and lower temperature variability and may have a physiological intolerance for warmer temperatures (Zielinski et al. 2017). Pacific marten prefer cooler, moister, and snowier areas relative to the fisher (Zielinski et al. 2017). Spencer et al. (2015b) found that annual precipitation and mean maximum temperature best predict marten distribution, meaning marten are sensitive to changes in these variables. Zielinski et al. (2017) did not detect marten in areas with less than 35.9 inches of annual precipitation and the majority were detected at sites that received at least 40.9 inches of precipitation annually. Sites with minimum annual temperatures less than 37.2 °F were the most likely places to detect martens. Thus, increases in temperature and decreases in precipitation can restrict marten distribution.

Range shifts have been observed for several California small mammal taxa over the past century. Work comparing historic (1914-1920; (Grinnell and Storer 1924); the "Grinnell transects") and contemporary (Moritz et al. 2008) small mammal surveys conducted in Yosemite National Park by UC Berkeley's Museum of Vertebrate Zoology (MVZ), came to several conclusions: (1) the elevation limits of geographic ranges shifted primarily upward, and (2) several high-elevation species (e.g., alpine chipmunk [*Tamias alpinus*]) exhibited range contraction (shifted their lower range limit upslope), while several low-elevation species expanded their range upslope (Moritz et al. 2008).

An alternate response to warming spring trends is the adjustment of breeding and migratory phenology in birds. Earlier breeding can limit exposure to warm temperature anomalies, which reduce nest success in warmer range limits (Socolar et al. 2017). Advancement of the breeding phenology of California bird communities 5-18 days earlier has been observed over the past century (Socolar et al. 2017, Saracco et al. 2019). Such shifts may be evidence of climate adaptation in the form of temperature tracking, as earlier breeding can substitute for range shifts to cooler temperatures (Socolar et al. 2017). Together, these studies suggest that some wildlife are already responding to changing climates to maintain environmental associations to which they are adapted.

Many native fish species, such as trout species (Salmonidae) and sculpins (Cottidae), require cold water to survive and do poorly at water temperatures >72˚F (22˚C) (Moyle et al. 2013). For cold-water adapted species such as salmonids, warmer water temperatures can lower egg viability, and lead to higher vulnerability to disease and predation (Sauter et al. 2001, Schaaf et al. 2017). Warmer temperatures may also favor salmonid predators and invasive species over natives (Sauter et al. 2001, Moyle et al. 2013). Fish do have some ability to acclimate to warmer temperatures than what they would normally prefer, but this ability varies between species (Sauter et al. 2001). Even within a single species such as Chinook salmon (*Oncorhynchus tshawytscha*), thermal preferences vary between individuals and life stages (Zillig et al. 2021). As with bird species, there are likely to be some fish that benefit from warmer water

temperatures, while others face increased stress. For example, early ice-break dates at Castle Lake in northern California have been associated with warmer water temperatures near the lake shore, and lower fitness of brook trout (*Salvelinus fontinalis*). This is because the warmer water temperatures caused the trout to not utilize lake habitat or consume the abundant food sources found in the lake, so that they instead remained in the ocean and relied on scarcer food sources (Caldwell et al. 2020). On the other hand, warmer water temperatures have been shown to benefit the growth of juvenile coho salmon (*Oncorhynchus kisutch*) in northern California, mainly because the positive effects from more abundant prey outweighed the negative effects of thermal stress (Lusardi et al. 2020).

Indirect impacts

Alterations to community dynamics

Direct responses to climate change can result in indirect impacts to other species. Shifts in range can in turn lead to the formation of novel species assemblages, resulting in altered community dynamics. Many species will face new competition and/or predation pressures, alterations in prey availability, or shifting disease and parasitism dynamics that may negatively impact them (Stralberg et al. 2009). Climate change can also lead to indirect impacts to wildlife by altering habitat. Over the last century, changes in climate have affected wildlife habitat in northwestern California both directly (e.g., through moisture-stress inducted mortality of trees) and indirectly (e.g., through loss of habitat to severe fire; see vegetation section for more detail).

While species exhibiting range contraction or upslope shifts are likely limited by thermal tolerance and contraction of suitable habitat (e.g. alpine chipmunk and Sonoma chipmunk [*Tamias senex*]), those with stable or expanding distributions (e.g. lodgepole chipmunk [*T. speciosus*]) may have been released from interspecific competition by retreating species (Rubidge et al. 2011). Extirpation of climate-sensitive ecosystem engineers and keystone species (e.g., American pika) from thermally stressful sites may also dramatically alter ecosystem ability to support certain species and assemblages (Beever et al. 2011).

Wildlife may also be indirectly impacted by climate change through reduction of populations and distribution of prey species. Decreases in moisture due either to decreases in precipitation or increases in temperature which outweigh stable or increasing precipitation may reduce production of plants, seeds, and fungi that are important food for spotted owl prey species, such as wood rats (*Neotoma* spp.) and flying squirrels (*Glaucomys sabrinus*) (Seamans et al. 2002, Olson et al. 2004, Glenn et al. 2010, Glenn et al. 2011). Jones et al. (2016b) suggest that the higher California spotted owl sensitivity to warmer temperatures in areas with cooler microclimates (e.g., high elevations) may be more related to effects of these climate variables on the distribution and abundance of prey species than their direct physiological impact on the owls themselves. Drought conditions may reduce production of the fungi that makes up more than three quarters of flying squirrel summer diet (Maser et al. 1985, Jones et al. 2016b). Additionally, Keane et al. (2006) found that northern goshawk reproduction was greatest in years following high cone crop production, which positively affected Douglas squirrel (*Tamiasciurus douglasii*) abundance. Warming trends and extended drought have the potential to decrease cone crop production (Redmond et al. 2012), potentially leading to deleterious effects throughout the food web. Lastly, O'Shea et al. (2016) described large mortality events in bats in drier regions linked to drought-induced starvation due to food shortages.

Another major indirect impact of climate change on wildlife populations is the loss of synchrony between reproductive or migratory phenology and resource availability (MacMynowski and Root 2007). Though alteration to phenology could be due to temperature sensitivity as discussed above, it may also be an indirect response to prey availability or habitat coverage, as insects emerge earlier or as trees begin to flower and leaf earlier with warming spring temperatures (Saracco et al. 2019). However, changes in phenology can lead to mismatches in critical life-stages (e.g., egg laying) and resource availability, which may in turn affect nest success and population persistence if birds cannot successfully track both thermal niche and resource emergence (Socolar et al. 2017). Long-lived mammals may be more likely than short-lived mammals to experience loss of synchrony between phenology and resource availability. This is because short-lived mammals tend to base their reproduction on cues such as temperature and resource availability, while long-lived mammals tend to base reproduction on photoperiod (Bronson 2009). Thus, short-lived mammals may be more able to adapt to changes in the timing of resource availability. As the loss of synchrony between reproductive or migratory phenology and resource availability becomes more pronounced, for species like bats that have specialized diets and carefully balanced energy budgets (e.g., Pallid and Townsend's big-eared bats on the Mendocino), a shift in the timing of invertebrate prey availability could result in reduced survival or fecundity (Halofsky et al. 2011b). Fish, similar to many other species groups, may also experience loss of synchrony at various life stages. Asch (2015) found that the timing of larval fish and the zooplankton they rely on for food may be experiencing disconnects.

Breeding dates of birds like tree swallows (*Tachycineta bicolor*) have advanced during the last century (in the tree swallow case, they now occur up to 9 days earlier; Dunn and Winkler (1999)) which may lead to a mismatch in timing of egg laying relative to availability of food. Shifted flowering, fruiting, and seeding times may affect species that rely on these services. Timing of the migration of California overwintering songbirds like Swainson's thrush (*Catharus ustulatus*), warbling vireo (*Vireo gilvus*), and Wilson's warbler (*Cardellina pusilla*) among others has also advanced significantly since 1969 (MacMynowski and Root 2007). Asynchrony with animal and insect pollinators may also become a significant problem for California plant species (Memmott et al. 2007).

Changes in habitat quantity, quality, and distribution

Alterations to habitat are another indirect climate impact on wildlife species. While upwards range shifts for high-elevation small mammal species are consistent with predicted climate warming, changes in lower- to mid-elevation species' ranges are more likely the result of habitat alteration from landscape-level vegetation dynamics related primarily to fire history (Moritz et al. 2008, Santos et al. 2017).

Certain habitats may become increasingly rare and/or unstable under climate change, with impacts for the species that depend on those habitats. For example, old growth specialists such as the NSO may see loss of habitat as fire behavior intensifies. In mixed-severity fires that burned the Klamath-Siskiyou in 2013, over 93% of NSO habitat that burned at high severity was no longer suitable habitat (Lesmeister et al. 2019). Throughout most of the range for NSO, suitable habitat is moist old-growth forests that tend to be fire resistant and are less likely to burn at moderate or high severity than the surrounding landscape (Lesmeister et al. 2019, Lesmeister et al. 2021). However, the forests of the Shasta-Trinity are drier than most other NSO habitat and may be at greater risk for high-severity fire, especially as the climate grows warmer. Restoration treatments, including thinning, prescribed fire, and wildland fire use, can reduce risk

of high-severity fire and provide other co-benefits to water availability, biodiversity, and carbon stability in seasonally dry forests of California (Stephens et al. 2020).

Species that rely on wetland habitat may also face challenges from drought and fluctuating water availability. For example, the black tern (*Chlidonias niger*) depends on emergent vegetation in wetlands, which may be absent if water levels are either too high or too low. The species has already seen population declines of 8.4% annually in the Klamath Basin over 2001-2010 (Stephens and Rockwell 2015) and is at risk for further declines if the availability and/or quality of wetland habitat declines.

Halofsky et al. (2011a) ranked habitat specialists like the NSO and American marten, and species like Clark's nutcracker (*Nucifraga columbiana*) that inhabit sensitive habitat, as highly vulnerable to climate change. Declines in marbled murrelet (*Brachyramphus marmoratus*) populations early this century may be partially attributable to loss of nesting habitat to increasing disturbances like fire. In other areas in the western US, decreasing songbird diversity and abundance has been indirectly attributed to decreasing snowfall patterns (Martin and Maron 2012). Low rates of snowfall allow for increased over-winter herbivory by ungulates like elk (*Cervus* spp.), thus decreasing growth and abundance of some tree species, in turn decreasing associated songbird abundances (Martin 2007, Brodie et al. 2012, Martin and Maron). Increased water temperatures promote populations of parasites like copepods, which negatively affect the fitness of fish and amphibian species (Kupferberg et al. 2009). Species like the protected foothill yellow-legged frog (*Rana boylii*) have been shown to suffer higher outbreaks of copepod parasites with increased water temperatures and drought induced decreases in water flows in northern California (Kupferberg et al. 2009).

Species like Pacific fisher and spotted owl rely on large, tall trees for the structure they provide (e.g., for nesting or denning) and the microclimates and predator protection they create (through the high canopy cover levels). As noted in the vegetation section, there have been high mortality rates of trees throughout California, including higher than expected and accelerating rates of loss of the largest size classes on which these species depend (e.g., >36 in DBH) (Smith et al. 2005, Lutz et al. 2009a, McIntyre et al. 2015). Thompson et al. (2020) suggest that approximately 40% of fisher habitat in the southern Sierra has been lost through the cascading effects of drought, insect infestation, fire, and subsequent tree mortality. Partially due to these habitat impacts, the Southern Sierra Distinct Population Segment of Pacific fisher was recently listed as endangered by the U.S Fish and Wildlife Service on June 15th, 2020 ([50 CFR 17.11](h)).

In addition to high drought-related mortality of large trees critical for some wildlife species, larger, high-severity fires have also impacted wildlife habitat, particularly over the last half-century (see fire section). High-severity fires reduce canopy cover and basal area, and often result in mortality of large trees (Lydersen et al. 2016), reducing the late seral forest habitat on which spotted owls and fishers depend. Though California spotted owls may be adapted to and use small high-severity patches (Kramer et al. 2021), increased proportions of high-severity fire are associated with large high-severity patches with lower CSO occupancy, colonization, and habitat use (Roberts et al. 2011, Tempel et al. 2014, Eyes et al. 2017, Jones et al. 2020, Schofield et al. 2020, Kramer et al. 2021), and higher CSO extinction probability (Lee et al. 2013) over the last two decades. Where greater than half of CSO territory burned at high-severity in the 2014 King Fire in the Sierra Nevada, territory extinction rates went up seven times, and occupancy declined nine-fold from pre-fire values (Jones et al. 2016a). In Yosemite National Park,

California spotted owls avoided areas of the Rim Fire characterized by more than 30% high severity fire (Schofield et al. 2020). From 1993 to 2013, approximately 88,000 acres (15%) of CSO protected activity centers burned and 28% of burned area was high severity (Gutiérrez et al. 2017). While this was similar to the severely burned area on the overall landscape (26%) during this period (Gutiérrez et al. 2017), it is greater than would be expected under a more natural fire regime (less than 5-15%) (Mallek et al. 2013). NSOs are also negatively impacted by high-severity fire, with lower survival and habitat suitability in areas impacted by high fire severities (Rockweit et al. 2017, Lesmeister et al. 2019). Mixed-severity fires that burn at primarily low severity with some high-severity patches seem to have little effect on NSO survival and recruitment (Rockweit et al. 2017). Fuel treatments to reduce fire severity can benefit both NSOs (Ager et al. 2007) and California spotted owls (Jones et al. 2022).

Future Climate Projections

Temperature

Like historical trends, average temperature is predicted to increase on the Shasta-Trinity National Forest under both RCP 4.5 and 8.5 scenarios (Table 4, Figure 7). Annual average maximum temperatures are projected to increase by 1.2°F to 3.1°F in the early part of the century (2010-2039) and by 5.3°F to 10.3°F by the end of the century (2070-2099) (Table 4). Annual average minimum temperature, which is generally synonymous with annual average nighttime temperature, is projected to increase by 2.6°F to 4.1°F in the early part of the century (2010-2039) and by 4.4°F to 10.7°F by the end of the century (2070-2099) (Table 4).

Increasing temperatures result in a greater number of days and nights above freezing (Figure 8). The magnitude of these changes is greater in the upper elevation watershed (Coffee Creek Watershed, Figure 8). By the end of the century, in the upper elevation watershed, where freezing temperatures are even more critical to maintain snowpack, the average number of nights above freezing increases by 77 days (113 to 190 days), while the average number of days above freezing increases by 19 days (343 to 362 days). By the end of the century, in the lower elevation watershed (Pit River Arm-Shasta Lake watershed), the average number of nights above freezing increases by 38 days (315 to 353 days). Historically in the lower elevation watershed, there are no days below freezing therefore this will not change.

Table 4. Modeled historical and future average minimum and maximum temperature on the Shasta-Trinity National Forest summarized for 30-year periods for emission scenarios RCP 4.5 and 8.5. Difference between projected future temperature compared to modeled historical (1950-1979) temperature is presented in parentheses.

Climate Metric	Value	1950-1979	1980-2005	2010-2039		2040-2069		2070-2099	
		Historical		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Annual Average Maximum Temperature (°F)	Min.	58.7	59.2	61.4 (+2.7)	59.8 (+1.2)	63.2 (+4.5)	62.5 (+3.8)	64.0 (+5.3)	66.3 (+7.6)
	Ave.	61.8	62.4	64.6 (+2.8)	64.9 (+3.1)	66.2 (+4.5)	67.5 (+5.7)	67.5 (+5.8)	70.8 (+9.1)
	Max.	65.3	65.3	67.7 (+2.4)	68.0 (+2.7)	70.2 (+5.0)	72.1 (+6.8)	71.9 (+6.7)	75.6 (+10.3)
Annual Average Minimum Temperature (°F)	Min.	29.4	30.8	32.8 (+3.4)	32.4 (+3.1)	33.3 (+3.9)	33.1 (+3.7)	33.8 (+4.4)	36.6 (+7.2)
	Ave.	32.4	33.0	35.0 (+2.6)	35.4 (+3.0)	36.5 (+4.1)	37.8 (+5.4)	37.7 (+5.2)	41.2 (+8.8)
	Max.	34.8	36.7	38.7 (+3.9)	38.9 (+4.1)	39.4 (+4.7)	41.9 (+7.1)	40.7 (+5.9)	45.5 (+10.7)

Modeled data were collected from CalAdapt and are based on LOCA downscaled climate projections (Scripps Institution of Oceanography) using an average of the 4 priority models for California (Bedsworth et al. 2018): HadGEM2-ES, CNRM-CM5, CanESM2, and MIROC5.
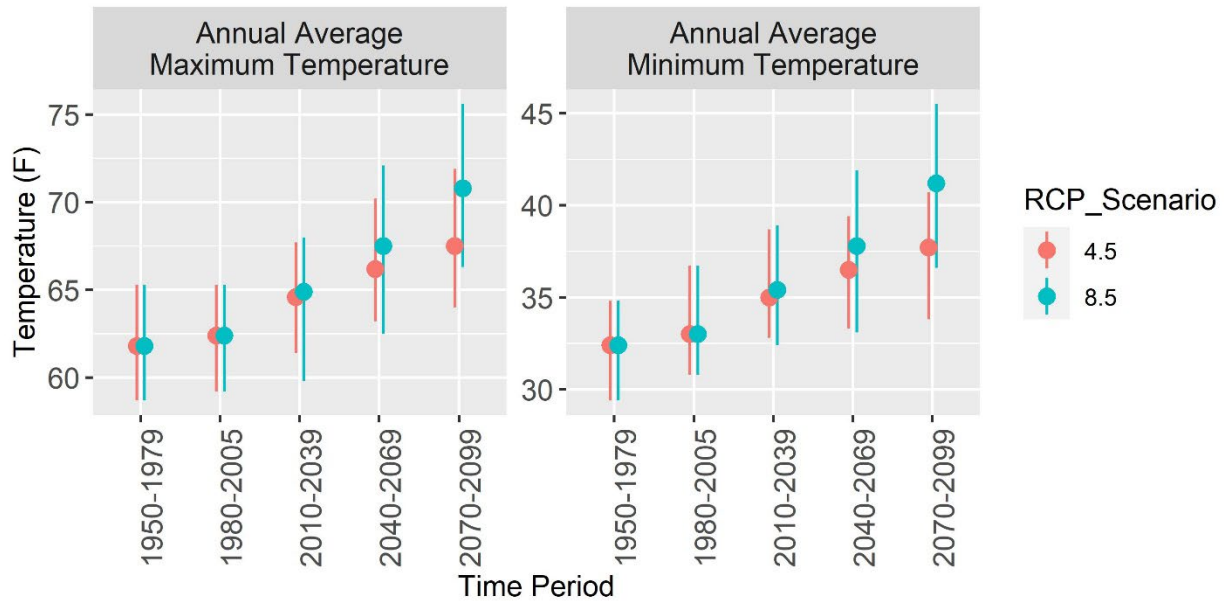

Figure 7. Modeled historical and future average minimum and maximum temperature on the Shasta-Trinity National Forest summarized for 30-year periods. Points represent average while lines indicate range of data (minimum and maximum). Data source CalAdapt: see Table 4 footnote.
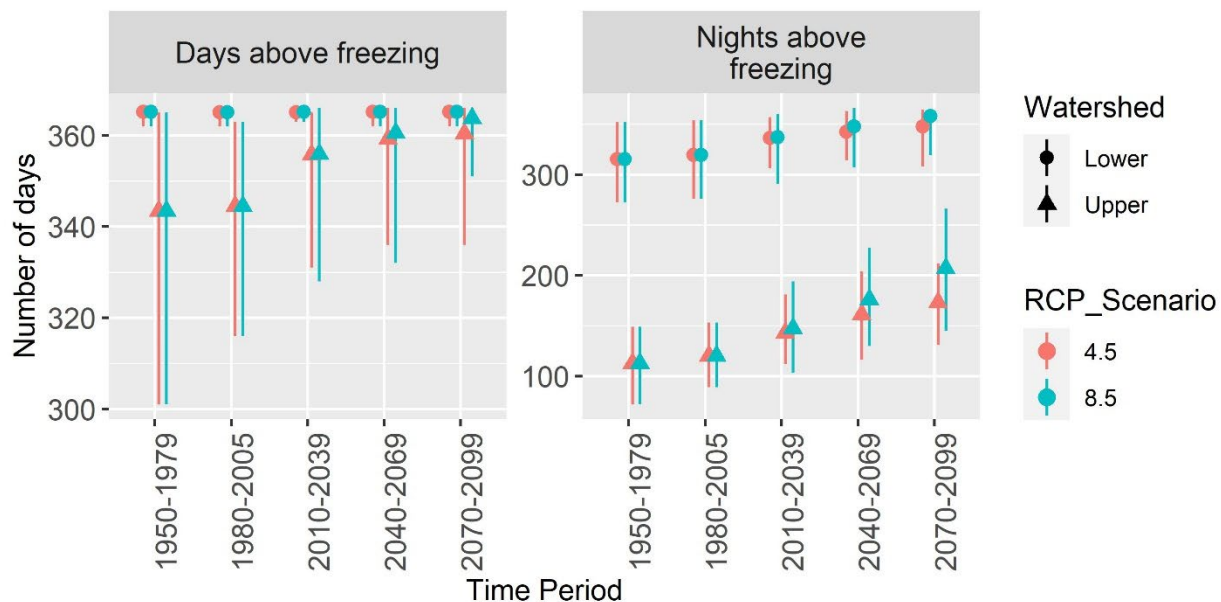
Figure 8. Modeled number of days above freezing (32°F) for the Coffee Creek Watershed (upper) and Pit River Arm-Shasta Lake Watershed (lower) on the Shasta-Trinity National Forest summarized for 30-year periods. Points represent the average while lines indicate range of data. Data source CalAdapt: see Table 4 footnote. Days above freezing and nights above freezing are based on when the daily maximum/minimum exceeds 32°F.

The increases in predicted future temperature on the Shasta-Trinity National Forest are consistent with predicted changes for California. While the magnitude of warming varies by both model and emission scenario, California's mean temperature is projected to increase by 3.6-12.6°F by the end of this century (Pierce et al. 2018). As temperature increases, the freezing line, which marks the transition from snow to rain, will also rise in elevation (Rhoades et al. 2018).

Extreme heat

As temperatures increase so will the number of extreme heat events and warm nights. The change in extreme heat days is predicted to be greater for the upper elevation watershed (Coffee Creek Watershed, Figure 9). By the end of the century, in the upper elevation watershed the average number of warm nights increases by 49.1 days (from 3.4 to 52.5 days), while the average number of extreme heat days increases by 41.8 days (from 4.2 to 46 days). By the end of the century, in the lower elevation watershed (Pit River Arm-Shasta Lake Watershed) the average number of warm nights increases by 52.5 days (from 3.5 to 56 days), while the average number of extreme heat days increases by 38.6 days (from 3.5 to 42.1 days).
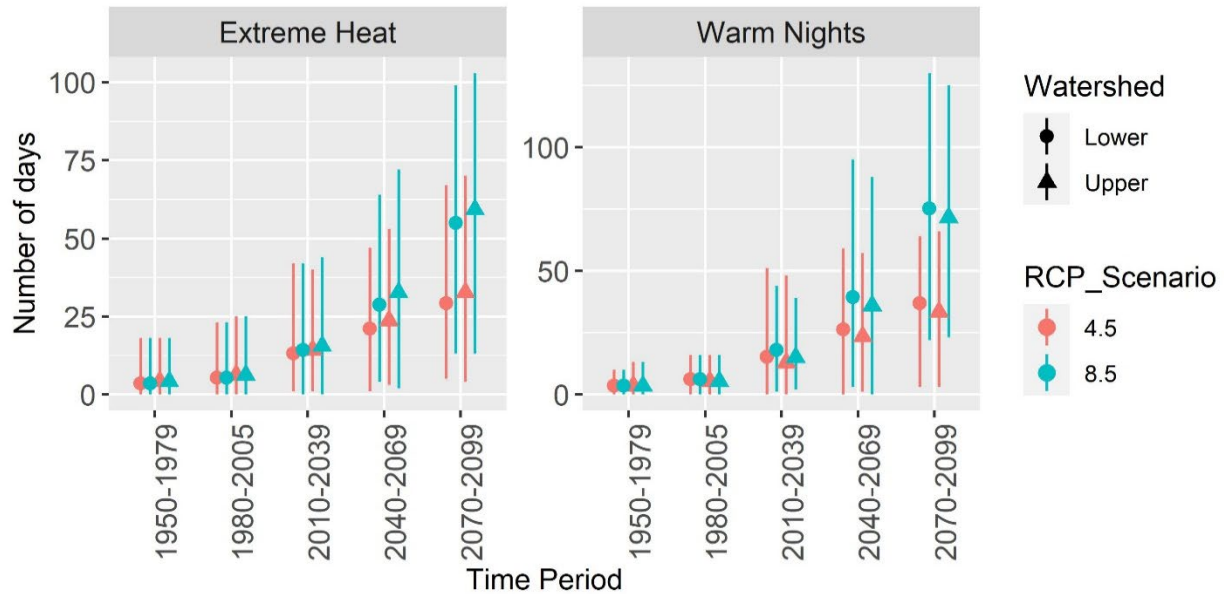
Figure 9. Modeled extreme heat days and warm nights for the Coffee Creek Watershed (upper) and the Pit River Arm-Shasta Lake Watershed (lower) on the Shasta-Trinity National Forest summarized for 30-year periods. Points represent the average while lines indicate range of data. Data is based on the 98th percentile temperature between April and October. The 98th percentile for extreme heat (max. temp.) is 88.4°F for the Coffee Creek Watershed and 102.3°F for the Pit River Arm-Shasta Lake Watershed. 98th percentile for warm nights (min. temp.) is 46.6°F and 66.1°F for the Coffee Creek Watershed and the Pit River Arm-Shasta Lake Watershed, respectively. Data source CalAdapt: see Table 4 footnote.

Precipitation

Like historical patterns, predicted changes in annual precipitation across the Shasta-Trinity National Forest are variable with a large range in annual minimum and maximum precipitation (Figure 10). Predicted trends in precipitation are highly variable under both RCP 4.5 and 8.5 scenarios (Table 5, Figure 10). Annual average maximum precipitation is projected to decrease by up to 7.5 inches in the early part of the century (2010-2039) but then either increase by 4.5 inches or decrease by 5.8 inches by the end of the century (2070-2099) depending on the climate scenario considered (Table 5).

The high degree of variation in precipitation is in part driven by the frequency of extreme precipitation events, ranging from zero to 17 events predicted for a single year (Figure 11). Due to the large degree of interannual variability in the occurrence of extreme events, there is predicted to be a minimal increase in average number of extreme precipitation events (2.4 in 1950-1979 to 3.8 in the upper watershed in 2070-2099). Similarly, there was only a minor increase in the maximum number of annual events from 7 events in 1950-1979 to 8 events in 2070-2099 in the lower watershed and from 11 events to 13 events in the upper watershed. While the number of extreme events only increases slightly, the intensity of extreme precipitation events is predicted to increase more dramatically (Figure 12). By the end of the century total rainfall occurring in extreme precipitation events could increase by 2.5 inches (total average of 13.8 to 16.3 in) in the lower watershed and by 5.5 inches in the upper watershed (total average of 18.7 in to 24.2 in) (Figure 12).

Table 5. Modeled historical and future annual average precipitation on the Shasta-Trinity National Forest summarized for 30-year periods for emission scenarios RCP 4.5 and 8.5. Difference between projected future precipitation compared to historical (1950-1979) precipitation is presented in parentheses.

Climate Metric	Value	1950-1979	1980-2005	2010-2039		2040-2069		2070-2099	
		Historical		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
	Min.	22.3	26.1	30.7 (+8.4)	28.2 (+5.9)	30.4 (+8.0)	17.1 (-5.2)	27.8 (+5.4)	27.7 (+5.4)
Annual Average Precipitation (inches)	**Ave.**	57.9	58.2	60.4 (+2.4)	61.0 (+3.1)	60.7 (+2.7)	60.1 (+2.2)	60.3 (+2.4)	64.6 (+6.7)
	Max.	122.1	92.0	115.2 (-6.8)	114.6 (-7.5)	121.6 (-0.5)	114.0 (-8.0)	126.6 (+4.5)	116.2 (-5.8)

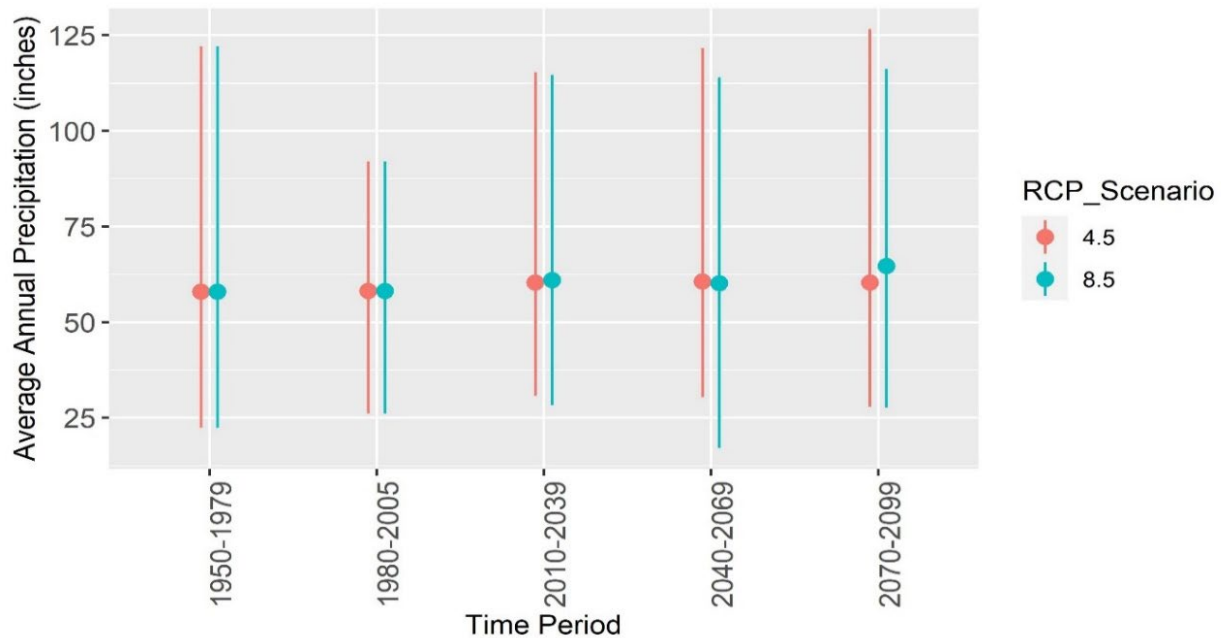Data source CalAdapt: Table 4 footnote.

Figure 10. Modeled historic and future average annual precipitation on the Shasta-Trinity National Forest summarized for 30-year periods. Points represent average while lines indicate range of data (minimum and maximum). Data source CalAdapt: See Table 4 footnote.
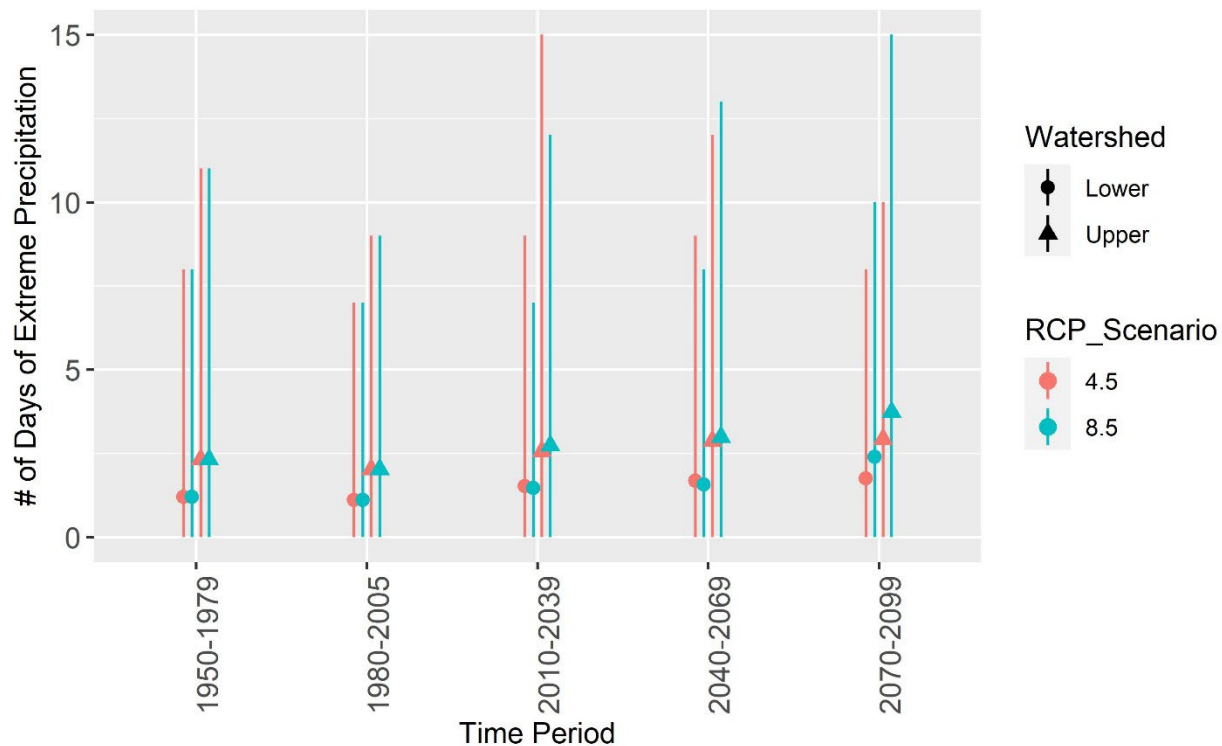
Figure 11. Modeled number of days of extreme precipitation in a water year with 2-day rainfall totals above the extreme threshold for the Coffee Creek Watershed (2.96 inches) and the Pit River Arm-Shasta Lake Watershed (2.83 inches) on the Shasta-Trinity National Forest summarized for 30-year periods. Points represent average, while lines indicate the minimum and maximum. Data source CalAdapt: See Table 4 footnote.

There is a lot of uncertainty in modeled future precipitation. GCM projections of precipitation across California tend to disagree on the sign of change and projected trends throughout the 21st century are generally insignificant (e.g. Neelin et al. 2013, Berg and Hall 2015). The year to year variability in precipitation is projected to increase, leading to both more dry years and wet extremes (Pierce et al. 2018). Berg and Hall's (2015) analysis of 34 global climate models project that wet seasons that become extremely dry will become roughly 1.5-2 times more common and wet extremes will generally triple in frequency by the end of the century. The increase in precipitation is predicted to occur primarily in winter precipitation (+20%), while decreases are predicted for spring and autumn (-20%) (Pierce et al. 2018). Additionally, daily extreme precipitation values are projected to increase by 5-20%, depending on the model and emission scenario (Pierce et al. 2018).
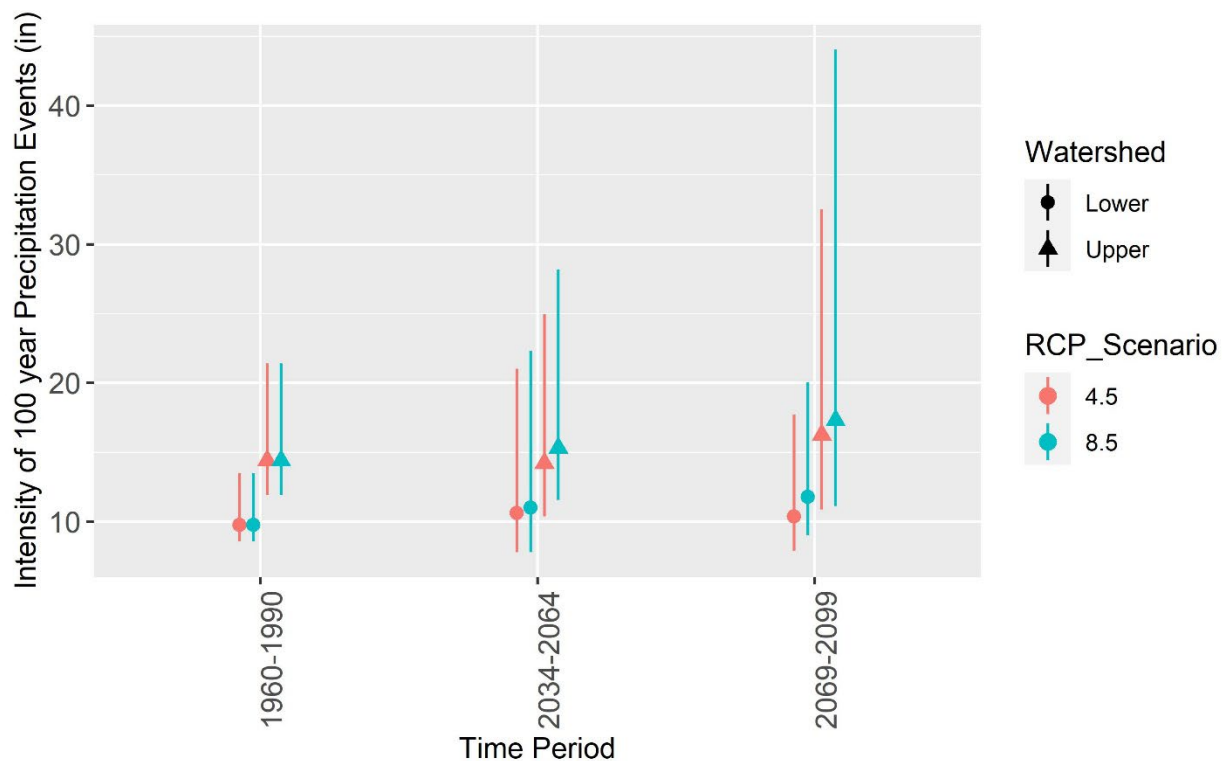
Figure 12. Modeled intensity of extreme precipitation events that on average occur every 100 years for the Upper Watershed (Coffee Creek Watershed, 2.00 inches) and the Lower Watershed (Pit River Arm-Shasta Lake Watershed, 0.80 inches) on the Shasta-Trinity National Forest summarized for 30-year periods. Points represent average, while lines indicate the maximum upper and maximum lower 95% confidence interval. Data source CalAdapt: See Table 4 footnote.

Hydrology

Snowfall

Snow water equivalent is projected to decrease across the Shasta-Trinity National Forest (Table 6, Figure 13) over the coming century. By the end of the century (2070-2099) there will be a projected decrease of 8.2-9.8 inches of SWE (Table 6, Figure 13). This decline in SWE is due to a decreased snow-to-rain ratio (Huang et al. 2018).

Future predicted snowpack declines for the Shasta-Trinity National Forest are similar to predicted changes for California. As climate warms, snowpack will dramatically diminish with only the highest peaks maintaining historical levels of snow by mid-century (Pierce and Cayan 2013). Research from Yosemite predicts that seasonal snowline may rise 980 feet in elevation for each 3.6℉ increase in temperature. Once temperatures increase by 7.2℉, areas below 6560 feet are projected to be snow free (Roche et al. 2018). Similar results may be seen across the western U.S., where the rain-snow transition zone is expected to move up in elevation, resulting in 24-53% less land area receiving snow (Klos et al. 2014). Berg and Hall (2017) estimate future snowpack declines of 60-85% due to anthropogenic warming. Rhoades et al. (2018) project that western US mountain snowfall will decrease by 30%, snow cover will decrease by

44% and SWE will decrease by 69%. Additionally, the date of peak snowmelt is projected to occur from 3 to 24 days earlier in the season (Hayhoe et al. 2004).

Snowpack is predicted to decline across elevational gradients with peak snow melt occurring earlier at middle and higher elevations (Ishida et al. 2018, Ishida et al. 2019). According to Micheli et al. (2018), the North Coast region is predicted to see a drop in April 1 extent of snow from 60% to 11% by the end of the century under a warm, moderate rainfall climate scenario, with the Klamath watershed management area (WMA) expected to be the most vulnerable to snow losses with an expected decrease in April 1 snow extent from 91% of the WMA to 16% by the end of the century. The April 1 SWE is expected to be less than 10% of historical levels, dropping from an average of 10.3 inches (1951-1980) to 1 inch by the end of the century (2070-2099) (Micheli et al. 2018).

Table 6: Historical and modeled future average annual April 1st Snow Water Equivalent (SWE) presented in inches on the Shasta-Trinity National Forest summarized for 30-year periods for emission scenarios RCP 4.5 and 8.5. Difference between projected future SWE compared to observed historical (1950-1979) SWE is presented in parentheses.

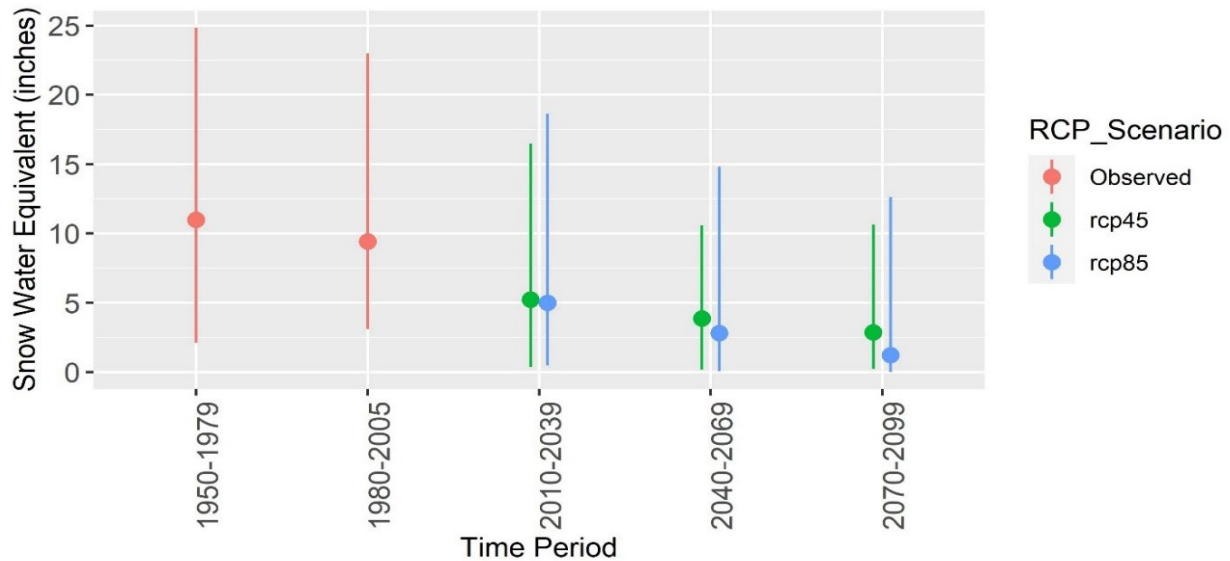| Model	1950-1979	1980-2005	2010-2039	2040-2069	2070-2099
Observed	11.0	9.4 (-1.6)	-	-	-
RCP 4.5	-	-	5.2 (-5.8)	3.9 (-7.1)	2.8 (-8.2)
RCP 8.5	-	-	5.0 (-6)	2.8 (-8.2)	1.2 (-9.8)

Data source CalAdapt: See Table 4 footnote.

Figure 13. Historical observed and future predicted April 1st Snow Water Equivalent (SWE) on the Shasta-Trinity National Forest summarized for 30-year periods under two emission scenarios (RCP 4.5 and RCP 8.5). Points represent average while lines indicate range of data (minimum and maximum). Data source CalAdapt: See Table 4 footnote.

Snowmelt timing/peak runoff

Future climate related hydrological changes anticipated in the mountains of northern California and subsequent downstream basins are much more substantial than what has already been documented to-date. These hydrological changes will have wide-ranging impacts to forest health, wildfire, wildlife species, human water supplies, hydropower production and public health that extend beyond California. Projected changes will include increased interannual hydrological variability. For instance, the Central Valley, one of the world's richest agricultural regions, is both more vulnerable to higher flood risk in higher precipitation years and lower water supply due to climate change effects in the upper watersheds that feed into it (He et al. 2019).

As warming trends continue with snow melting earlier and more precipitation falling as rain, water will exit mountain catchments earlier (Harpold et al. 2015) and consequentially lead to less water available to plants and lower stream volumes later in the year. Researchers project that under a high emission climate scenario, the Cascades will lose up to 81% of current April 1st SWE by the 2080s (Gergel et al. 2017). Modeling future hydrological changes in California, (Miller et al. 2003) found that annual streamflow volumes were strongly dependent on precipitation, but changes in seasonal runoff were more temperature dependent due to snowmelt timing and whether precipitation fell as snow or rain. Predicted spring and summer runoff was lower in all California river basins they modeled, except for model scenarios that projected increased precipitation, where runoff was unchanged from today (Miller et al. 2003). Runoff in the winter and early spring was predicted to be higher under most climate scenarios because higher temperatures will cause snow to melt earlier. Timing of peak flow is projected to occur up to seven weeks earlier by 2100, depending on the climate scenario (Young et al. 2009).

Soil moisture

Warming temperatures will increase evaporative demands resulting in a potential increase of 10-19% in climatic water deficit (CWD) by mid-century and 16-32% by the end of the century for the North Coast region, causing extreme drought stress in soils (Micheli et al. 2018). A study in the Sierra Nevada projects there to be a >15% decline in fuel and soil moisture at both the lowest and highest elevations of the Sierra Nevada by the period ranging from 2070 to 2099 (Dettinger et al. 2018). This contrasts with findings for the historically moist mid-elevation zones, where future precipitation will come mostly as rain and soil moisture may increase from 20-40%. Less replenishment of soil moisture by snowpack will increase drought likelihood (Coats et al. 2013) and significantly affect the native flora in terms of species composition and structure.

Stream temperature and water quality

The hydrologic cycle and water quality are very sensitive to climate change in the headwater drainages of California (Luo et al. 2013). In northwest California, stream temperatures have increased by 0.2-0.9˚F over recent decades, and may increase a further 0.8–1.4°F by 2080 (Hilberg and Kershner 2021a). Rising stream temperatures will cause dissolved oxygen to diminish, creating inhospitable conditions for cold-water fish species and reducing the extent of cold water habitat (Ficklin et al. 2013). Isaak et al. (2018) used three warming scenarios to classify potential losses in river habitat for brown trout (*Salmo trutta*) and rainbow trout (*Oncorhynchus mykiss*). Rivers in northwestern California showed the largest potential losses compared to baseline out of the entire study area, with a potential decrease ranging from 13% with a

temperature increase of 1.8°F to a 47% decrease with a temperature increase of 3.6°F. High stream temperatures are also expected to occur for longer (30-60 more days per year in 2090 with water temperatures above 68°F) creating unfavorable conditions for cold-water species (Null et al. 2013).

Streamflow volume and variability

Future projections for streamflow suggest an overall decrease in stream volume, particularly in dry months and extended summer drought periods (Reba et al. 2011). Increased variability in streamflow in California is already resulting in – and is predicted to continue to result in – extended wet and dry spells (Pagano and Garen 2005), with significant economic, social, and biological impacts (Mote et al. 2005). Using a suite of climate change models, Grantham (2018) predicted that stream flows in the North Coast region will decrease in the dry season and increase in the wet season, with January seeing the greatest increase and May seeing the greatest decrease in flows. In basins without winter snow accumulation, such as the Eel River basin, base flow is relatively insensitive to increasing temperature (Miller et al. 2003). If precipitation does increase, streamflow volumes during high flow events could greatly increase. Flood potential in California rivers that are fed principally by snowmelt (i.e., higher elevation streams) are predicted to increase under all scenarios of climate change, principally due to earlier dates of peak daily flows and the increase in the proportion of precipitation falling as rain (Miller et al. 2003). Under continued snowpack loss, Knowles and Cayan (2002) project that spring and early summer flows on the upper Sacramento River may decrease by as much as 30% by 2060, and that annual flow volume could drop by 20% by 2090; more snow-dominated river basins may see much greater changes. Between -41 and +16% more variability in streamflow volume is projected in California's major water supply watersheds (He et al. 2019). Projections for the Sacramento River under the RCP 8.5 scenario when looking at total annual unimpaired flows in a water year (October – September) for June, July, and August show a high degree of variability with the warmer and drier scenario showing the sharpest decline in streamflow (Figure 14). Because of the relatively low mountain elevations in NW California, stream flow in most rivers is more sensitive to changes in precipitation than changes in temperature, as snowpack input to flow is relatively low (Miller et al. 2003).
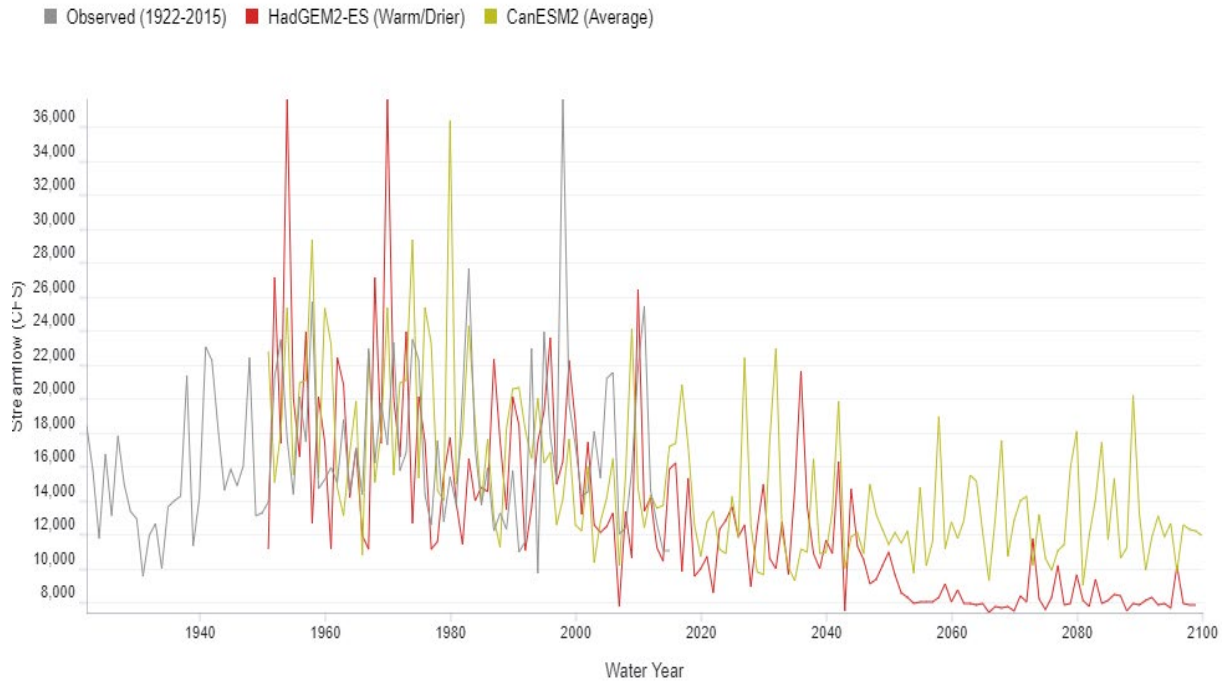
Figure 14. This chart shows total annual unimpaired flows in a water year (October – September) for June, July, and August. Data are shown for Sacramento River near Red Bluff under the RCP 8.5 scenario in which emissions continue to rise strongly through 2050 and plateau around 2100. Values represent observed streamflow (1922-2015) and global climate models (GCM) of CanESM2 (an average simulation) and HadGEM2-ES (a warm/drier simulation).

Flooding and atmospheric rivers

While generally less surface water overall is projected, increases in extreme flooding events are also forecasted, adding to the challenge of managing public lands and downstream water uses in the future. Atmospheric rivers are going to become larger contributors to the amount of total precipitation across California, as precipitation from other sources dwindle leading to increasing precipitation variability (Gershunov et al. 2019). Increases in extreme hydrologic events across the western U.S. are predicted to be especially pronounced in the mountains of the California coast range and the Sierra Nevada (Kim 2005). In the Russian River, all seven floods that exceeded the monitor stage[7] between 1997 and 2006 were linked to atmospheric rivers (Ralph et al. 2006). In California, several studies have connected post-fire debris flows (Oakley et al. 2017) and landslides (Oakley et al. 2018) to the incidence of landfalling atmospheric rivers, either in their interaction with water-resistant wildfire burn scars or by saturation of the soil. The potential for secondary hazards that outweigh the initial impact of atmospheric rivers is also

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[7] Monitor stage is the water level above some arbitrary reference elevation called the datum. It is not the same as depth but is used to identify the potential for flooding.

possible. Such events could facilitate unprecedented debris flow and landslide events within the region, such as those documented in headwater streams in the Klamath Mountains (Cover et al. 2010).

More flooding in higher-elevation, snowmelt-fed California rivers is also projected under all scenarios of climate change, principally due to earlier dates of peak daily flows and the increase in the proportion of precipitation falling as rain (Miller et al. 2003). There is scientific consensus that flood regimes in historically snow-dominated mountainous regions will shift from spring snowmelt-driven events toward more frequent rain-dominated winter floods (Hirabayashi et al. 2013, Arnell and Gosling 2016). The risk of rain-on-snow events, and associated destructive and costly flooding, are also predicted to increase in the future throughout the mountains of northern California (Musselman et al. 2018).

Drought

Climate change is projected to further amplify evapotranspiration and moisture overdraft as precipitation becomes more erratic (Swain et al. 2018, Goulden and Bales 2019). In addition, temperatures are predicted to continue to increase across California. Increasing temperatures will exacerbate drought impacts and will likely lead to higher tree mortality, especially in areas with higher tree density and greater climatic water deficit (Young et al. 2017). Using 21st century projections of warming and the RCP8.5 emissions scenario, total snowpack is projected to decline by 85% during this century (Berg and Hall 2017). Like most western states, mountain snowpacks are a critical resource in California, and supply water for multiple uses throughout much of the state. Strong environmental gradients in California result in wide variation in ecosystems, drought sensitivities, and constraints and opportunities for management responses. Fettig et al. (2019b) provides drought management strategies by major California ecosystem types.

Periods of extended drought will make the Shasta-Trinity National Forest hotter and drier. Moisture deficit is projected to increase over much of the state, which will cause a decrease in soil moisture especially in the southern half of the state (Pierce et al. 2018). During periods of drought there will be an increase in the average minimum and maximum temperature, a decrease in average precipitation, a decrease in snow, and a decrease in baseflow (portion of the stream flow that is not from precipitation and results from seepage of water from the ground) and runoff (water that is discharged into the streams and largely results from precipitation and melting of snow) (Table 7).

Table 7. Climatic response to periods of drought during a midcentury dry spell (2023-2042) and a late century dry spell (2051–2070) identified from the HadGEM2-ES RCP 8.5 simulation for two watersheds on the Shasta-Trinity National Forest. Historical data (1961-1990) are based on observed values. The extended drought value equates to 78% of historical median annual precipitation averaged over the North Coast and Sierra California Climate Tracker regions.

Metric	Coffee Creek Watershed			Pit River Arm Shasta Lake Watershed		
	1961-1990	2023-2042	2051-2070	1961-1990	2023-2042	2051-2070
Ave Maximum Temperature (°F)	56.4	61.3	65.0	70.6	75.2	78.8
Ave Minimum Temperature (°F)	26.6	30.4	34.0	44.4	48.4	51.9
Ave Precipitation (in)	74.7	60.4	60.4	61.3	49.4	49.4
Snow Water Equivalent (in)	4895.2	1968.5	735.6	22.7	7.4	1.5
Baseflow (in)	27.5	20.6	19.9	17.5	11.1	10.3
Runoff (in)	22.9	13.9	13.1	14.8	10.0	9.9

Modeled data were collected from CalAdapt based on LOCA downscaled climate projections (Scripps Institution of Oceanography) using the HadGEM2-ES RCP 8.5.

While future changes in climate and associated hydrologic changes may seem bleak, managers have an opportunity to proactively manage to sustain or restore hydrologic function and to plan for future conditions. Stream hydrological function and meadows can be restored to reduce vulnerability to a change in climate. Previously incised meadows restored at the onset of the 2012-2016 drought were shown to have improved summer baseflow (by 5 to 12 times) throughout the drought compared to wetter, non-drought years (Hunt et al. 2018). The use of beaver dam analogs (BDAs; instream structures that mimic natural beaver dams) or other process-based techniques can be another effective way to meet restoration goals in areas where beaver reintroduction is not feasible or not appropriate (Pollock et al. 2014). The first location in California where BDAs have been installed is in the Scott River basin of northern California (Charnley 2018).

Future Fire Activity and Severity

Current trends of increasing fire activity and severity are predicted to continue. Several comprehensive reviews of the wildland fire literature for the western US have found overwhelming evidence that area burned and number of fires will increase, and fire seasons will be longer, as the climate warms (Flannigan et al. 2009, Restaino and Safford 2018). A number of studies focused on California have projected significant increases in wildfire activity in association with climate change, particularly for forest vegetation types (Lenihan et al. 2008, Westerling and Bryant 2008). Westerling and Bryant (2008) projected a 10-35% increase in large fire risk by mid-century in California and Nevada. Spracklen et al. (2009) projected that the total area burned across the western US would increase by 54% in 2046–2055 relative to 1996–2005.

For California's fourth Climate Change assessment, Westerling (2018) simulated fire activity across California from 1953 to 2099 (Figure 15). Model results under the high emission (RCP 8.5) scenario project a 77% increase in mean area burned and a 178% increase in the maximum area burned across California by the end of the century, compared with the 1961-1990 period. Under the high emission scenario, extreme wildfires (> 250,000 acres) were projected to occur 50% more frequently, with montane forests in the northern two thirds of the state expected to experience the greatest increases in annual average acres burned by the end of century (Figure 15).

For the two selected watersheds on the Shasta-Trinity National Forest, data compiled by Westerling (2018) also project that total acres burned will generally increase by the end of this century, despite some variation in the lower elevation watershed (Figure 16). For the lower elevation watershed, Pit River Arm-Shasta Lake, historical (1954-1979) averages of between 2034 and 2039 acres burned annually which are projected to either decrease to 1638 or increase to 3248 acres burning annually by the end of the century depending on the climate scenario. In the higher elevation Coffee Creek watershed, historical annual averages of between 981 and 996 acres burned are projected to increase to between 1997 and 2731 acres burned annually by the end of the century. Acres burned appear to follow a cyclical pattern, with years of high area burned followed by periods of low area burned. Declines in area burned may be due to lack of fuels, which would be consistent with fire modeling for California suggesting that loss of vegetation after fire may help to reduce the occurrence of large fires for a short time afterward (Hurteau et al. 2019). This may be especially true at lower elevations where fire activity is limited by fuels more than climate (Keeley and Syphard 2016).

Several models project that fire severity will also continue to increase in the western US throughout the 21st century (Abatzoglou and Williams 2016, McKenzie and Littell 2017, Abatzoglou et al. 2018). Future climate change may promote warmer and windier conditions, which would lead to higher fire intensity, faster fire spread, and more fires that escape containment in northern California (Fried et al. 2004). This effect explains some of the recent increase in California fires and is likely to lead to continuing future increases in fire frequency and area burned (William et al. 2019). Fire seasons may also grow longer, leading to further increases in area burned (Pausas 2004, Spracklen et al. 2009, Guyette et al. 2012, Wimberly and Liu 2014). Westerling et al. (2011) projected increases in burned area of up to 4+ times the current levels in northern California shrublands and forestlands by the end of the century. The MC1 runs reported in Barr et al. (2010) project increases in annual fire area in the Klamath River Basin of 11-22% by 2100, resulting in as many as 330,000 acres (134,000 ha) burned in an average year. Northern California may see some of the biggest increases in very large fires, compared to the rest of the United States, due to projected changes in temperature, precipitation, and relative humidity during the fire season (Barbero et al. 2015).
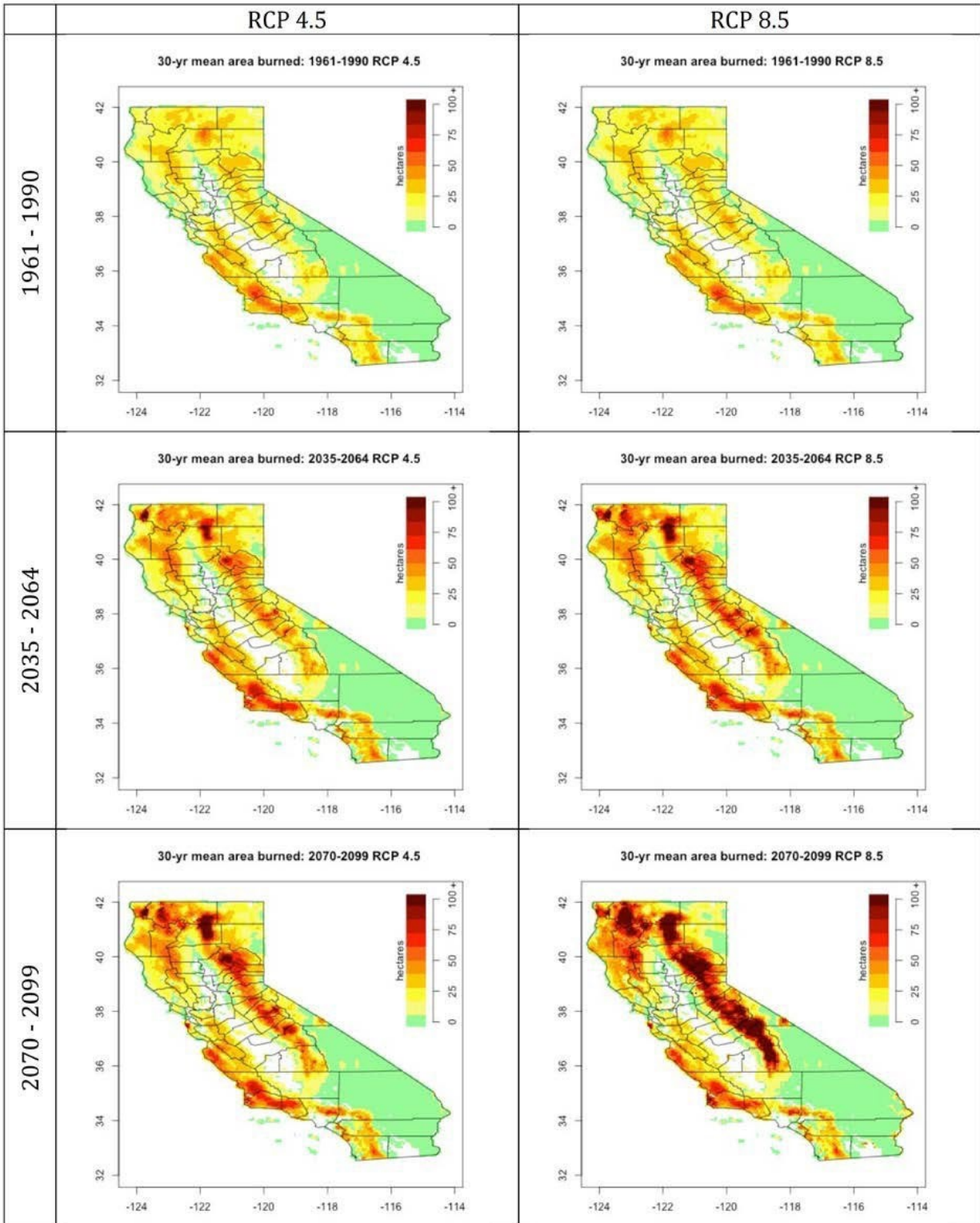
Figure 15. Average annual area burned composites: RCP 4.5 (left), RCP 8.5 (right) from Westerling (2018).
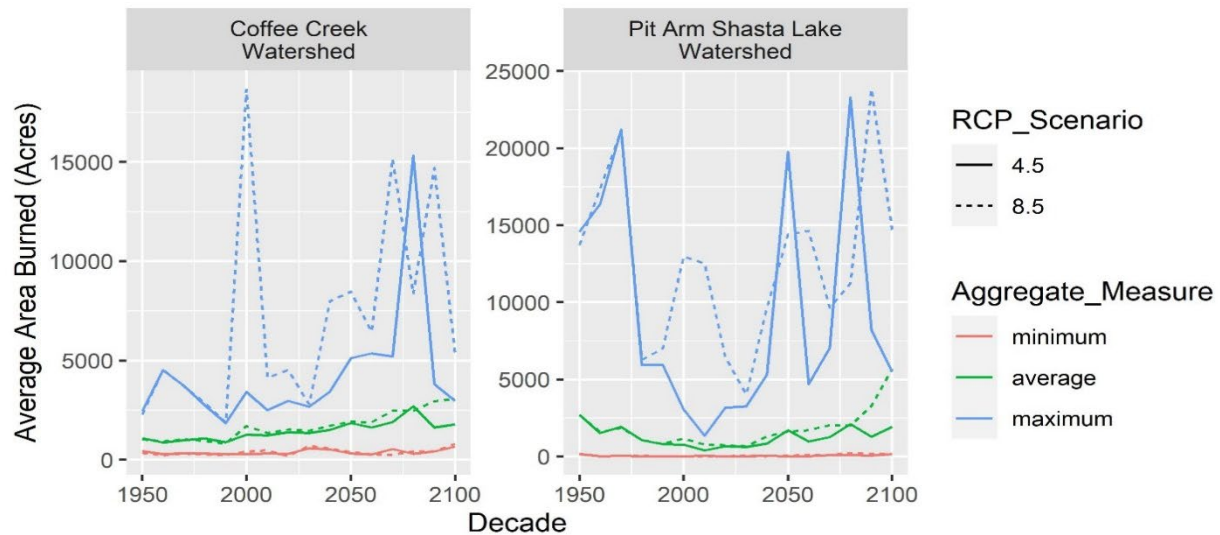
Figure 16. Wildfire simulations for two watersheds on the Shasta-Trinity National Forest smoothed by decade. Data source CalAdapt using wildfire scenario projections produced by Westerling (2018).

On the other hand, some models predict that increased fire activity may eventually decrease fire severity by reducing fuels and facilitating vegetation shifts towards more xeric, grass and shrubland vegetation types (Moritz et al. 2012, Batllori et al. 2013). Models developed by Parks et al. (2016) found that most areas of the western US would experience a reduction in fire severity by the mid-21st century, primarily as a result of higher water deficit reducing productivity and fuel production, making less biomass available to burn after widespread fires. Increased frequencies and/or intensities of fire in coniferous forest in California will almost certainly drive changes in tree species composition (Lenihan et al. 2003) and will likely reduce the size and extent of late-successional refugia (USFS and BLM 1994b, McKenzie et al. 2004). Thus, if fire becomes more active under future climates, there may be significant repercussions for old growth forest and old growth-dependent flora and fauna.

Use of paleoecological analogies also suggests that parts of the Pacific Northwest (including northern California) could experience more severe fire conditions under warmer, more CO_2-rich climates (Whitlock et al. 2003). Fire frequency and severity (or size) are usually assumed to be inversely related (Pickett and White 1985), and a number of researchers have demonstrated this relationship for California forests (e.g., Swetnam 1993, Miller and Urban 1999), but if fuels grow more rapidly and dry more rapidly – as is predicted under many future climate scenarios – then both severity and frequency may increase.

Projected temperature, fuel aridity, and fire season length

In the future, it is likely that increased temperatures will continue to result in increased fire activity (McKenzie et al. 2004, Spracklen et al. 2009, Guyette et al. 2012). Spracklen et al. (2009) concluded that temperature was primarily responsible for predicted increases in annual mean area burned in the western US, with some of the greatest increases projected for the Pacific Northwest ecozone, which includes northern California. It is also likely that increases in fuel aridity will continue to promote fire extent and severity in western US forests (Flannigan et al. 2013, Abatzoglou and Williams 2016, Abatzoglou et al. 2017, McKenzie and Littell 2017, Hurteau et al. 2019). Fuel amounts and continuity will also likely increase

with increasing CO_2 concentrations (Lenihan et al. 2003, Hayhoe et al. 2004, Lenihan et al. 2008). Paleoecological studies show that parts of the Pacific Northwest (including northern California) have experienced more severe fire conditions under warmer, more CO_2-rich climates in the past (Whitlock et al. 2003). Flannigan et al. (2013) projected that fire season length would increase by more than 20 days in northern California by 2100.

Projected snowpack effects and lightning activity

Fires may also become more frequent and severe because of reduced snowpack and increased lightning ignitions in the future. Declining snowpack may lead to decreases in summer soil moisture and dead fuel moisture, which can lead to increased fire potential, especially at higher elevations (Gergel et al. 2017). Even in areas without snow, increased surface temperatures are predicted to increase lightning activity. Price and Rind (1994) projected that a temperature increase of 7.6°F would result in a 44% increase in the number of lightning caused fires across the US, resulting in a 78% increase in area burned. Romps et al. (2014) also found that lightning could increase by 12% for every degree Celsius of temperature increase, resulting in a projected 50% increase in lightning-caused fires across the US by 2100.

Projected effects of tree mortality

Increased rates of tree mortality are also likely to promote fire activity in the future. As described in the vegetation section, warmer and drier conditions can stress trees and increase tree mortality rates (Miller et al. 2012, van Mantgem et al. 2013, Westerling 2016, van Mantgem et al. 2018). Widespread mortality of trees can increase fuel loads, as standing dead vegetation promotes canopy fire probabilities in the short term, while the accumulation of large dead woody surface fuels may increase the probability of large fires over longer time frames (Stephens et al. 2018, Westerling 2018, Coop et al. 2020, Stephens et al. 2022).

Future Vegetation Projections

Future climate change will have direct effects on vegetation (Breshears et al. 2005) and intensify stressors such as fire and drought contributing to indirect effects on vegetation in a constant disturbance feedback loop (Hurteau et al. 2019). Although there is considerable certainty that vegetation distribution, composition, and structure will change, there is uncertainty as to the catalyst for change. Buotte et al. (2019) used a Community Land Model to determine vulnerability to mortality from drought and fire by 2049. They found vulnerability to both future fire and drought will be high in the Sierra Nevada and the Klamath Mountains (Buotte et al. 2019). Because mortality has the potential to lead to changes in forest composition and transitions to non-forest vegetation types (Veblen et al. 1991, Allen and Breshears 1998, Anderegg et al. 2013, Williams et al. 2013), vulnerability estimates in Buotte et al. (2019) indicate these forested regions have the potential to experience substantial ecological change in the coming decades. Lowest total vulnerability to either drought or fire is anticipated in the wettest types such as Coastal Douglas-fir, western hemlock (*Tsuga heterophylla*), incense cedar, and redwood (*Sequoia sempervirens*) forest types (Buotte et al. 2019).

Distribution of vegetation

The distribution of vegetation in California is generally expected to move upslope and poleward in response to climate change (Hayhoe et al. 2004, Loarie et al. 2008). However, the intensity of projected changes in climate, as represented by emission levels and changes in temperature and moisture, is increasingly important to consider during strategic landscape planning. Strategic management decisions, whether to maintain historical species, land-cover types, ecosystem processes, and resources; or to embrace and foster changes predicted by changing climates (Millar and Stephenson 2015), carry risk. Managing for current attributes and enhancing resilience to changing climate may be a wasted effort if climate change and secondary effects such as increasing wildfire (Miller et al. 2012) overwhelm the capacity of systems to be resilient. In contrast, managing for vegetation change could place species at risk if future climate projections used to set management objectives turn out to be inaccurate, and thereby encourage transition strategies that do not fit the new climate (Swanston et al. 2016). Uncertainty arises from variation among climate models, imperfect understanding of vegetation responses to climate, and complex direct (physiological) and indirect vegetation responses that interact through physical disturbance (i.e., fire) as well as through biotic pathways (i.e., pests and pathogens).

Loarie et al. (2008) projected that two-thirds of California's native flora will experience >80% reduction in range size by 2100. Endemic plant species that specialize in uncommon or sparsely distributed habitat (e.g., serpentine soils, montane meadows) will have difficulty responding to changing climatic conditions by migrating (Conlisk et al. 2013). Such narrowly distributed species are also at high risk due to disturbances like fires or floods that may extirpate entire populations. Conversely, areas resistant to change, such as north facing slopes or areas with deep, well-watered soils, may provide potential refugia (Olson et al. 2012, van Mantgem and Sarr 2015). Topographic microclimates play an important role in species distributions (Randin et al. 2009, Scherrer and Korner 2011, Lenoir et al. 2013). In the Klamath region, if warming climatic trends are accompanied by drying during the growing season, mesic topographic microclimates are likely to become increasingly important microrefugia (Dobrowski 2011, Copeland and Harrison 2015).

Structure and composition of forests

Climate will have direct effects on vegetation by modifying the niche space for certain species while indirectly enhancing wildfire activity and drought intensity, which will both lead to changes in vegetation composition and structure. Change in tree species cover will be delayed relative to changes in climate in forested systems since long lived tree species can persist despite conditions not being favorable for recruitment (Loarie et al. 2009). As climate changes, regeneration rates may initially improve for ponderosa pine but then will begin to decline in 2060-2099, with the biggest declines in warm and/or low-elevation areas (Petrie et al. 2017). Ponderosa pine may begin to move to higher elevations, while high-elevation species such as lodgepole pine or western white pine (*Pinus monticola*) may have limited refugia or opportunities for range shifts (Bell et al. 2014, Maxwell and Scheller 2020). Lenihan and colleagues (Lenihan et al. 2003, Lenihan et al. 2008) projected significant declines in conifer-dominated forests and their subsequent replacement by hardwood-dominated forests along the northern California Coast Range under all future climate scenarios. In the drier interior northern California Coast Range, they projected declines in shrubland and oak woodlands and an increase in grassland due to higher fire frequencies;

hardwood-dominated forests also increase in area. Future increases in drought may lead to changes in the diversity and structure of old growth stands (van Mantgem and Sarr 2015).

Although gradual stand replacement will result in forest ecosystem conversion, it is more likely that disturbance events predicted to be more common under a future climate will drive more rapid vegetation changes (Batllori et al. 2017, Thorne et al. 2017). As disturbance such as fire is projected to increase in intensity and size, woody plants that resprout after disturbance are projected to do well (Davis et al. 2018, Westerling 2018). However, the persistence of these vegetation types will be determined by recovery time between disturbances as shorter fire return intervals would lead to even more rapid and widespread vegetation replacement (Davis et al. 2018). Increases in the size of high severity patches in fires would exacerbate already reduced conifer recruitment as distance to cone bearing trees increases (Shive et al. 2018). This reduction in recruitment can be even more pronounced following extreme drought periods (Stevens et al. 2017, Young et al. 2019).

Some climate models project decreasing precipitation and increasing aridity likely leading to moisture conditions that may cause vegetation transitions, particularly in post fire landscapes (Parks et al. 2016, Serra-Diaz et al. 2018). These climate models project an increase in grassland area at lower and middle elevations, as woody vegetation retracts in the face of increased fire frequency and invasion by non-native annual grasses (Dodson and Root 2015, Parks et al. 2018).

Climate vulnerability is defined as exposure, sensitivity and adaptive capacity to a changing climate and can be used to help assess susceptibility of major forest types in northwestern California to climate and related stressors. Thorne et al. (2017) evaluated forest type vulnerability across California under four future climate scenarios representing an increase of 1.9 – 4.5°C and either a decrease or increase in precipitation (-24.8 to +22.9%). Between the hot/dry model (MIROC-ESM) and the hot/wet model (CNRM CM5), there is consensus that in the Shasta-Trinity National Forest, climate conditions are expected to cause high stress for existing vegetation over the next century, with 21% of the landscape at high stress between 2011-2039, 33% by 2040-2069 and 40% by 2070-2099 at emission level RCP8.5 (Figure 17). Thorne et al. (2018) assessed climate exposure and vulnerability of ten major forest types across California, Nevada, Utah, Arizona, and New Mexico in 2070. Not all vegetation types were equally exposed and vulnerable with lower elevation ponderosa pine and eastside Jeffrey being only moderately vulnerable, and higher elevation red fir forests being critically vulnerable across the Southwest (Thorne et al. 2018).
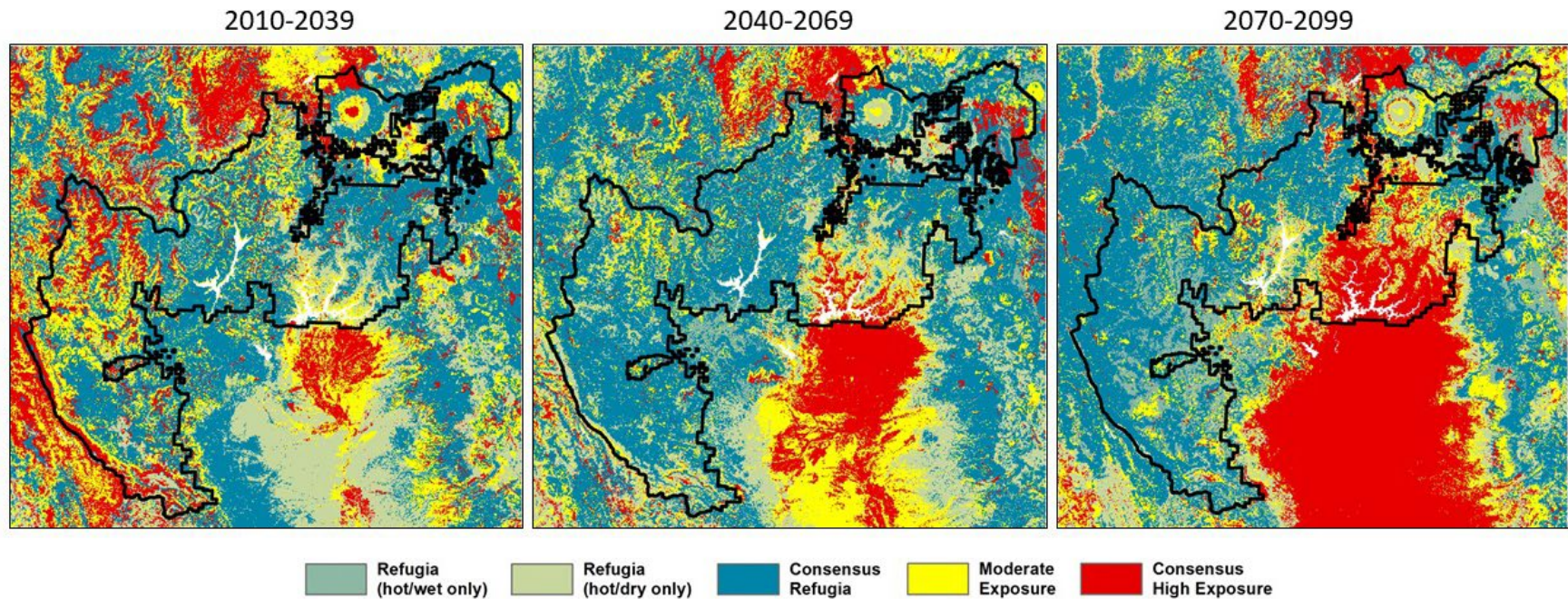
Figure 17. Mapped climate refugia and exposure using the "Hot and Wet" CNRM CM5 and "Hot and Dry" MIROC-ESM climate projections under Higher Emissions RCP8.5. This image shows five levels of climate exposure for vegetation across the Shasta-Trinity National Forest for three time periods: 2011–2039, 2040–2069, and 2070–2099. Areas of refugia have exposure values <80% and are considered to have climatically suitable conditions for the vegetation currently present. Moderate exposure areas have exposure values between 80-95%. High exposure areas have values >95% and are considered to have climatically unsuitable conditions for the vegetation currently present. Consensus areas are where both the "Hot and Wet" and "Hot and Dry" models agree, increasing the probability that those projected conditions will be present in the future.

Future Wildlife Projections

Direct impacts

Physiological effects and range shifts

Significant changes to California's wildlife populations are projected over the next century. Future range shifts are predicted to be larger than any historical range shifts, based on fossil records and climate reconstructions from the western United States over the past 17,000 years. Species with greater dispersal ability (e.g., larger mammals) may have the biggest range shifts and the best likelihood of finding desirable habitat as the climate changes (Williams and Blois 2018). In northwestern California, the biggest impacts to terrestrial wildlife may be due to loss of coniferous forests and corresponding increases in oak, chapparal, and montane hardwood vegetation. Both aquatic and terrestrial wildlife may also be impacted by lower stream flows, resulting in less water availability (PRBO Conservation Science 2011).

A total of 128 out of 358 (36%) of California's bird species of "special concern" (rare, threatened, endangered, or experiencing significant decline; Shuford and Gardali (2008)) were ranked as vulnerable to climate change, including the Swainson's hawk (*Buteo swainsoni*), western grebe (*Aechmophorus occidentalis*), Swainson's thrush, and Vaux's swift (*Chaetura vauxi*) (Gardali et al. 2012). Based on bioclimatic models, Lawler et al. (2009, 2010), projected high vulnerability of California's amphibian fauna (>50% change) and moderate vulnerability (10-40% change) of California's mammalian fauna under a high greenhouse gas emissions scenario by the end of the century. O'Shea et al. (2016) projected increases in large mortality events linked to drought and extreme weather events for susceptible species such as bats. Native fish species are also at high risk, with 82% of native fishes ranked as highly vulnerable to climate change. The species most at risk are those requiring low water temperatures. In comparison, only 12% of invasive fish species were ranked as highly vulnerable to climate change, and many invasives will likely see increases in range and population (Moyle et al. 2013).

Direct and indirect effects will continue to impact wildlife species in the future, likely at an accelerating pace. Lawler et al. (2012) investigated the possible effects of climate change on selected species of the genus *Martes* and found that macroclimate conditions closely correlated with Pacific fisher presence in California were likely to change greatly over the next century, resulting in a possibly pronounced loss of suitable habitat. Their results suggested that martens and fishers will be highly sensitive to climate change. A more recent analysis of climate impacts on fisher and marten habitat in the Sierra Nevada found that predicted marten distribution shifted to higher elevations, became more fragmented, and decreased in area by 40–85% (depending on GCM scenario; Spencer et al. 2015). On the other hand, predicted changes in fisher distribution were highly variable and inconsistent, showing some increases and some decreases in extent, suggesting high uncertainty in climate change effects on fishers (Spencer et al. 2015b). Population growth in northern spotted owls is positively associated with wet, cool summer conditions, likely an effect of prey availability, but climate models predict warmer, drier summers which will likely negatively impact spotted owl populations (Glenn et al. 2010). Additionally, NSO reproductive success may be negatively impacted by extreme climate events during their spring breeding season (Franklin et al. 2000), and NSOs may experience mortality or range shifts due to heat stress if maximum temperatures reach above 95.3˚F (35.2˚C) (Weathers et al. 2001).

Those aquatic species with a competitive advantage in colder waters will also likely suffer losses due to both thermal stress and increased competition as water temperatures rise (Rahel et al. 2008, Kennedy et al. 2009). Salmonids may be particularly sensitive to warming water temperatures (Boko et al. 2007). Power et al. (2015) suggested that two likely future scenarios (drier winters followed by drier summers; or wetter winters followed by drier summers) may trigger cyanobacteria blooms, harmful to salmonids and other fish. According to Power et al. (2015), "If dry winters are followed by dry summers, salmonids will be heat-stressed as well as hungry. The worst case appears to be if scouring winter flows release algal blooms, but abrupt decreases in summer baseflows cause these to rot in the channel as pools warm and stagnate." For aquatic species like steelhead and rainbow trout (*Oncorhynchus* spp.), decreases in August streamflow likely to be caused by increased CO_2 levels associated with climate change could have negative implications for habitat suitability and availability (Tague et al. 2009). Increased summer temperatures, and resulting declines in growth and productivity, are likely to further stress steelhead and rainbow trout populations like those in the low-order streams in the South Fork Trinity River basin (McCarthy et al. 2009). O'Neal (2002) suggested that by 2090, 25 to 41% of currently suitable California streams may be too warm to support trout.

Indirect impacts

Alterations to community dynamics

Stralberg (2009) developed current and future species distribution models for 60 focal bird species and found that novel avian assemblages with no modern analogue could occupy over half of California by 2070. This implies a dramatic reshuffling of avian communities and altered patterns of species interactions (Stralberg et al. 2009). As the loss of synchrony between reproductive or migratory phenology and resource availability becomes more pronounced, species like bats with specialized diets and carefully balanced energy budgets could experience reduced survival or fecundity due to a shift in the timing of invertebrate prey availability (Halofsky et al. 2011b). Further, increased temperatures can alter the transmission of sound through the air, affecting bats' ability to detect prey; echolocating bats with high frequencies (e.g. long-legged myotis [*Myotis Volans*], western red bat [*Lasirurs blossevillii*]) will likely experience declines in prey detection abilities as temperatures rise, while those with lower frequencies (e.g. pallid bat [*Antrozous pallidus*], Townsend's big-eared bat [*Corynorhinus townsendii*], fringed myotis [*Myotis thysanodes*]) may experience increased prey detection abilities, altering the balance of these predator-prey relationships (Luo et al. 2014).

Changes in habitat quantity, quality, and distribution

Species that require old, dense, and structurally complex forest conditions, like fisher and spotted owl, will likely be negatively impacted by changes in fire regimes and vegetation associated with climate change (Scheller et al. 2011). Projections suggest that much of the low- and mid-elevation forests that currently comprise owl and fisher habitat are vulnerable to conversion to woodlands, shrublands, and grasslands (see vegetation section). Projections of future climate and vegetation conditions (Bachelet et al. 2001, Lenihan et al. 2008), suggest a major decrease in suitable old forest mixed conifer habitat over the next 50 years (Spencer et al. 2015a), although the models may not adequately account for topographic effects on local microclimate and vegetation, which may partially mitigate the changes in mountainous terrain.

Increased fire frequencies, sizes, and intensities are likely to drive changes in tree species compositions (Lenihan et al. 2003, Lenihan et al. 2008) and reduce the extent of late-successional forests (USFS and BLM 1994a, McKenzie et al. 2004). These changes in forest structure could alter the extent, abundance or occurrence of species associated with these habitats, including the spotted owl (McKenzie et al. 2004, Purcell et al. 2012, Wan et al. 2019). Increases in area burned and proportion burned at high severity are likely to occur within the ranges of all three spotted owl species (northern, California, and Mexican spotted owls). Within the range of the northern spotted owl, Davis et al. (2015) estimated that 191,900 ha of nesting and roosting habitat on federal lands were lost to wildfires between 1994 and 2013. This area represented four times the amount of habitat considered lost from timber harvest (47,000 ha) and comprised 5.2% of the total habitat originally protected in 1994 (3,678,500 ha) under the Northwest Forest Plan (Davis et al. 2015). Research on NSOs in southwest Oregon suggests that survival decreased in the 3-5 years after fire, both for owls that returned to burned sites and owls that were displaced by burns (Clark et al. 2011). Mixed severity fire regimes can provide a beneficial patchwork of habitat for spotted owl nesting and foraging but increases in high and moderate fire severity patches may lead to decreased survival of spotted owls in northwest California (Rockweit et al. 2017). Impacts on spotted owls due to loss of nesting habitat could be compounded by loss of foraging habitat. Increased extent and frequency of high-severity fires will decrease habitat for prey species that depend on late seral forest, such as the northern flying squirrel (Wan et al. 2019). For northern goshawks, 80% of foraging habitat and 87% of roost locations have high fire hazard potential, so increases in fire frequency and severity will likely diminish goshawk habitat (Blakey et al. 2020).

Climate-change refugia exist along spatial and temporal continuums (Keppel et al. 2015), ranging from regional scales (where macrorefugia can facilitate ecosystem persistence over centuries and even millennia), to landscape and local scales (where microrefugia can maintain particular species and communities for years and decades), to hyper-local scales (where refuges can provide temporary shelter for individuals) (Fey et al. 2019). Species such as the American pika may increasingly rely on thermally stable microrefugia as the regional climate warms (Rodhouse et al. 2017). However, as these refugia disappear with a warming climate, population connectivity declines, and individual populations become more susceptible to extirpation. Thus, protection and maintenance of remaining refugia may aid population persistence, but eventually human-assisted migration may be the only option for maintaining population connectivity. Morelli et al. (2016) present a framework for managing refugia for climate change resistance and resilience. The authors emphasize the approach as a way for managers to prioritize areas for conservation and climate adaptation, particularly where refugial characteristics for a set of valued resources may coincide (Morelli et al. 2016). However, they also note that climate change refugia are not long-term solutions. Refugia might only be relevant for a certain degree of climatic change, after which they no longer support conditions necessary for the populations they were designed to protect. Thus, refugial management should be coupled with plans for more extreme climate change scenarios (Morelli et al. 2016). Loarie et al. (2008) identified the coastal mountains of northwestern California as an important climate change refugium, defined as an area projected to sustain species with otherwise shrinking ranges. Authors like Loarie et al. (2008) and Lawler and Olden (2011) recommend novel adaptive management approaches and large-scale planning efforts that promote landscape/regional habitat connectivity. Loarie et al. (2008) also recommended serious consideration of human-assisted dispersal of California's flora and prioritization of climate change refugia for conservation and restoration.

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Appendix A: Methods

Evaluating historical climate trends

Local trends in climate over the past century were summarized at the forest level from five local weather stations (WRCC 2022). Stations were chosen based on their geographic location to encompass a range of elevational gradients and on the length and completeness of their records. Records from these sites provide an indication of local-scale variation in climate patterns, and how patterns differ in the extent to which they reflect those seen at the broader forest and regional scales. Descriptions and locations of each weather station used in this report are provided in Figure 1 and Table 1 in the main body of this document. In addition to local weather station data, forest level climate data were compiled from the Climate Engine tool (http://climateengine.org/) using TerraClimate. TerraClimate combines high-spatial resolution climatological normals from WorldClim with coarser spatial data that have greater temporal information (Abatzoglou et al. 2018). We chose this data source because it provides annual averages from 1958-present and the stability of input stations was prioritized in the development of the Climatic Research Unit gridded Time Series (CRU TS) products, and therefore errors due to spurious trends from data collection are reduced.

For each of the weather stations, we evaluated the complete monthly climate records for trends in annual mean temperature, annual mean minimum temperature, annual mean maximum temperature, total annual precipitation, interannual precipitation variability, and total annual snowfall. We calculated temperature values for individual calendar year by first taking the average value across all days within each constituent month, and then averaging across the monthly averages. Individual years were excluded from temperature trend analyses if more than two months, or two consecutive months, lacked temperature data for more than 15 days. We calculated precipitation and snow totals for individual water-years (October 1st to September 30th) because water-year precipitation totals are more informative from a hydrologic perspective, particularly where precipitation that occurs as snow at the end of the calendar year typically doesn't drain from the watershed until the following spring or summer. Water year precipitation is more clearly linked to the availability of water for natural ecosystems and human populations during the annual summer droughts, and of greater importance for understanding flood risks to low-lying areas. Individual years were withheld from trend analyses if any month between October and April lacked precipitation data for more than five days. Interannual variability in precipitation totals were calculated as the coefficient of variation using a five-year moving window. Trend analyses were performed using only data from stations and time periods for which climate data were more than 70% complete. The presence, direction, and magnitude of climatic trends were assessed using a Mann Kendall test for serially correlated data (Mann 1945)[8].

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[8] The Mann Kendall test was used because it does not require data to be normally distributed and is capable of handling missing data. We used the method proposed by Hamed and Rao (1998) to adjust for temporal autocorrelation. All autocorrelation adjustments were implemented at the 95% confidence threshold. The non-parametric Theil-Sen slope estimator was utilized to determine the rate of change for each significant trend (Sen 1968). All trend analysis was done in R 3.6.1 using the package modifiedmk (Patakamuri and O'Brien 2017).

Evaluating future climate projections

The accumulation of carbon dioxide and other heat-trapping "greenhouse" gases influence how climate will change globally, regionally, and locally. Representative Concentration Pathways (RCPs) are scenarios that explore how future emissions and the resulting accumulation of greenhouse gases (GHGs) will drive changes in climate. They are defined by the net balance of radiation to and from the Earth's surface due to human emissions of GHGs (Pierce et al. 2018). Two RCP scenarios are presented in this report, RCP 8.5 and RCP 4.5. Future climate depends on future human behavior (Schwalm et al. 2020). Both scenarios are considered possible depending on how much action related to climate change mitigation occurs. RCP 8.5 is often called the business-as-usual scenario where atmospheric CO_2 concentrations continue to rise throughout the 21st century. RCP 4.5 is a scenario where GHG emissions rise until around 2040 and then decline, resulting in about 45% less CO_2 by 2100 compared to RCP 8.5 (Pierce et al. 2018). While both scenarios are plausible, recent CO_2 emissions (2005 to 2020) are within 1% of emission scenarios projected by RCP 8.5 and with continued economic growth, emissions may exceed RCP 8.5 scenario by 2100 (Schwalm et al. 2020).

The RCP scenarios are used in general circulation models (GCMs) to project future climate conditions. Few future-climate modeling efforts have treated areas as restricted as the State of California, and fewer still have covered a single National Forest. The principal limiting factor is the spatial scale of the GCMs that are used to simulate future climate scenarios. Most GCMs produce raster outputs with pixels that are 10,000's of km^2 in area. To be used at finer scales, these outputs must be downscaled using a series of algorithms and assumptions (Thrasher et al. 2013), adding uncertainty to already uncertain data. These finer-scale secondary products currently provide the most credible sources we have for estimating potential outcomes of long-term climate change for California. Another complication is the extent to which GCMs disagree with respect to the probable outcomes of climate change. For example, a comparison of 21 published GCM outputs that included California found that estimates of future precipitation ranged from a 26% increase per 1°C increase in temperature to an 8% decrease (Hakkarinen and Smith 2003, Gutowski et al. 2010). For this reason, we examine multiple different climate models in our projections of future climate.

There are currently 10 GCMs (out of more than 30) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) that have been identified as most suitable for California based on having a good simulation of California's historical climate (Bedsworth et al. 2018). The GCMs in combination with RCPs are used to simulate California's historical and projected future climate metrics (Bedsworth et al. 2018). While there are ten models for California, four models have been identified as "priority models" which were selected to capture the variability of the models: HadGEMS2-ES (warm/dry model), CNRM-CM5 (cool/wet model), CanESM2 (average model), and MIROC5 (T85 atmosphere – 1° ocean). These GCMs have been downscaled for California using the Localized Constructed Analogs (LOCA) method which increases resolution from a couple of grid cells for the entire state to a 3.7 mile grid cell (Pierce and Cayan 2017; Figure A-1). The LOCA method uses systematic historical effects of topography on local weather patterns, which attempts to preserve extreme hot days and heavy rain events. The increased resolution of LOCA captures varying wet and dry conditions across the state of California (Pierce et al. 2018).

Projected future climate data for this report were obtained from the Cal-Adapt (https://cal-adapt.org/) tools. The data cover 1950-2005 for the historical period and 2006-2100 for future climate projections.

We summarized LOCA downscaled climate projection data (Scripps Institution of Oceanography) for the

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History of Climate Modeling

Climate modeling has evolved over time. The first General Circulation Model (GCM) was published in 1956. In 1990, the Intergovernmental panel on climate change (IPCC) came out with their first report. In 1995, the Coupled Model Intercomparison Project (CMIP) was launched which established a standard experimental protocol coupling carbon and climate model simulations, which is still the foundation for climate modeling; to date there have been five CMIPs developed. By the end of the 1990's emission scenarios were coupled with climate models; to date there have been three types of emission scenarios developed. The 6th Assessment Report of the IPCC is now available and uses CMIP6 and an extended set of RCP scenarios paired with shared socioeconomic pathway (SSP) to better describe future socioeconomic, demographic, and technological trends. While climate modeling has evolved, older literature with previous GCM/CMIP and emission scenarios can still provide insight into future changes in climate.

Shasta-Trinity National Forest based on an average of the four priority models identified for California. Cal-Adapt summary data are not currently summarized by land ownership, including National Forest, so data were summarized for the Coffee Creek and the Pit River Arm-Shasta Lake watersheds. These watersheds were selected because they represent a range of elevation across the forest. The World Meteorological Organization recommends that climate be averaged (climate normal) using 30-year periods (NOAA 2020), so where applicable we present data in 30-year periods.
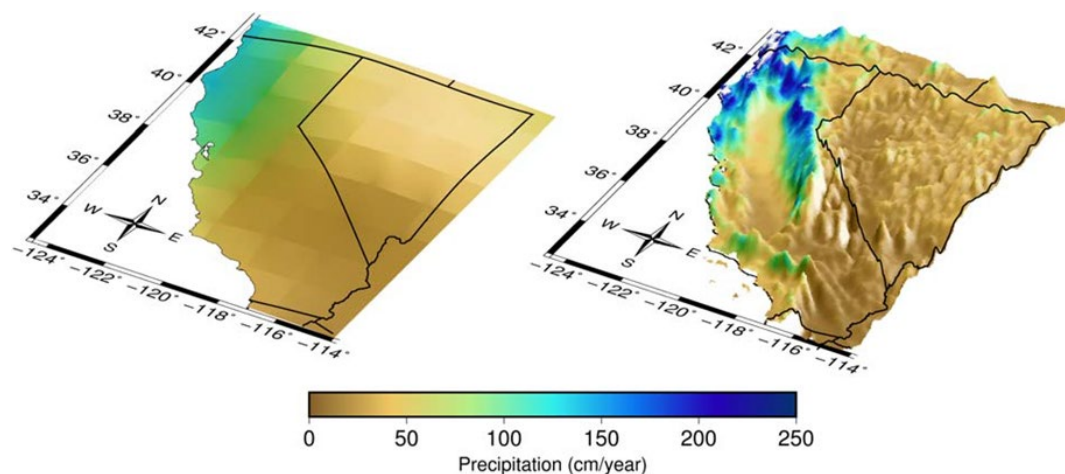

Figure A-1. Annual precipitation in California and Nevada (250 cm = ~100 inches). On the left is a global climate model with a resolution of 100 miles. On the right, downscaled model with a resolution of about 3.7 miles. Note how the downscaled model is better able to capture the variation in precipitation in northwestern California. Image was taken from (Pierce et al. 2018) where the vertical scale has been equally exaggerated in both images for clarity.

Appendix B: Additional Resources and Tools

Intergovernmental Panel on Climate Change (IPCC)

- Assessment reports
- Synthesis report of the Sixth Assessment Report

Northern California Climate Adaptation Products - EcoAdapt

- Overview of climate trends and projections
- Coastal Habitats
    - Summary
    - Coastal dune systems
    - Coastal bluffs and scrub
- Forest and Woodland Habitats
    - Summary
    - Habitats:
        - Black oak and tanoak woodlands
        - Coastal conifer-hardwood forests
        - Coastal redwood forests
        - Mixed conifer and ponderosa forests
        - Mixed evergreen forests
        - Oak savannas and open woodlands
        - Subalpine forests
        - True fir forests
    - Species:
        - Knobcone pine and cypress species
        - Late-successional-dependent species (e.g., Pacific fisher)
        - Marbled murrelet
        - Native ungulates
        - Pacific yew
        - Salamanders
        - Sugar pine
- Shrubland and Grassland Habitats
    - Summary
    - Habitats:
        - Alpine grasslands and shrublands
        - Chaparral shrublands
        - Mixed grasslands
    - Species:
        - Migratory birds

- - Native insect pollinators
- Freshwater Habitats
  - Summary
  - Habitats:
    - Freshwater marshes
    - Lakes and ponds
    - Rivers, streams, and floodplains
    - Seeps and springs
    - Vernal pools
    - Wet meadows and fens
  - Species:
    - Frogs
    - Native freshwater mussels
    - Northwestern pond turtle
    - Port-Orford cedar
    - Riparian-nesting birds
- Endemic Habitats
  - Habitats:
    - Endemic habitats (e.g., caves, cliffs, and talus slopes)
  - Species
    - Bats

USDA California Climate Hub

The USDA California Climate Hub mission is to help California land users (farmers, ranchers, forest landowners, and tribes) and land managers maintain sustainable communities and ecosystems by adapting to climate variability and change.

Western Regional Climate Center

The Regional Climate Centers (RCC) deliver climate services at national, regional, and state levels working with NOAA partners in the National Climatic Data Center, National Weather Service, the American Association of State Climatologists, the Regional Sciences and Assessment Program, and other NOAA Research Institutes. We also partner with the Department of Interior Climate Science Centers and Landscape Conservation Cooperatives.

The mission of the Western Regional Climate Center is to:

- Act as a repository of historical climate data and information
- Disseminate high quality climate data and information pertaining to the western United States
- Engage in applied research related to climate issues
- Improve the coordination of climate-related activities at state, regional and national scales

Natural Climate Solutions Data Atlas

The Natural Climate Solutions Data Atlas is a web-based visualization tool to showcase the geospatial data generated by the Center for Ecosystem Climate Solutions (CECS) for California's terrestrial ecosystems. The Atlas consists of annual records of disturbance, water balance, vegetation stress, carbon dynamics, fuels, and ignition probability spanning a timeframe from 1986 to 2021, at 30-m to statewide resolution. Data layers are sourced from Landsat (30-m grids) and transformed into ecosystem services with transparent physical units using our natural ecosystem modeling Data Engine to track water, vegetation stress, fire, and carbon as a wholistic web of tightly-linked ecological conditions. This allows for apples-to-apples comparisons across space and time. CECS data products are created with scientific software on the leading edge of reproducibility, rapid refresh, and continuous improvement.

The Data Atlas was developed as part of CECS, a project supported by the California Strategic Growth Council's Climate Change Research Program with funds from California Climate Investments—Cap-and-Trade Dollars at Work. CECS is developing actionable, science-based tools to help California manage its natural lands in the face of climate change. More information is available online at https://california-ecosystem-climate.solutions/.