Stanislaus National Forest Climate Change Trend Summary

Region 5 Ecology Program
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Image Caption: View of Cherry Lake on the Stanislaus National Forest.

Summary

As with across the globe, the climate of California is in a stage of rapid flux compared to historical precedent. This document highlights past, current, and projected climate change on the Stanislaus National Forest. It is divided into two sections. The first section documents climate change-related trends that have occurred over the last century for the forest. The second section details projected future trends for the forest. This trend summary is produced by the US Forest Service Pacific Southwest Region (R5) Ecology Program to inform national forest managers on climate change-related ecosystem vulnerabilities to plan for and where possible, mitigate. Climate change trend summaries are currently available for all the National Forests of California and are updated regularly (~ every five years) as new climate science becomes available.

The climate is changing on the Stanislaus National Forest. Average temperatures have increased over the last century, with the greatest increase occurring in nighttime temperatures. The increase in temperature has lengthened the frost-free period by two to three months. There is a high degree of interannual variability in precipitation, often with dry years following wet years. The water contained in the snowpack has declined by more than 50% on much of the Sierra Nevada landscape. Drought periods have become more frequent due to a combination of low precipitation and high temperatures. Climate models project that temperatures will continue to rise, with the annual average minimum temperature increasing by up to 11°F by the end of the century. Increasing temperatures will further reduce the number of days and nights below freezing and will cause a rise in the elevation at which rain transitions to snow (the "freezing line"). The number of extreme heat days and warm nights will notably increase. Trends in precipitation will continue to be influenced by high interannual variability, with total precipitation predicted to increase by up to 19 inches depending on the climate model and emission scenario. The high degree of variation in precipitation is in part driven by the frequency of extreme precipitation events, ranging from zero to 19 in any given year. The intensity of extreme precipitation events is also projected to increase. While total precipitation is projected to increase, average annual snow water equivalent is projected to decrease by up to 7 inches. Periods of extended drought combined with increasing temperatures will make the Stanislaus National Forest hotter and drier.

Sierra Nevada hydrological conditions are rapidly changing as the climate warms. Less precipitation is falling as snow and the reduced snowpack is melting earlier and exiting the mountains more quickly, leaving less water available to mountain ecosystems and biota. A changing climate will only continue to alter hydrology into the future. Peak runoff is projected to occur even earlier and streamflow volumes will continue to decrease, punctuated by extreme high-flow flooding events that may cause landslides, mass erosion, and increase risk to human infrastructure and lives. As temperatures rise, stream temperatures will also increase, which along with decreasing water quality, will have serious consequences for aquatic species and terrestrial animals that depend on aquatic ecosystems. To ameliorate these impacts, the most effective strategies will include those that reduce water loss from the mountains system either by slowing drainage through meadow and stream restoration and beaver reintroduction, or by minimizing evapotranspiration through reduction of forest densities.

Climate is also a primary driver of fire activity, particularly through the effects of temperature and precipitation on factors such as fuel moisture and abundance, fire season length, storm activity, snowpack, drought stress and tree mortality. Wildfire activity has dramatically increased across the western United States over the past four decades, including area burned, fire frequency, total fire number and the number of large fires, fire season length and fire severity. Trends of increasing fire activity and severity are predicted to continue into the future. Future emissions scenarios will largely determine wildfire activity, human activities (particularly population growth and land-use change) will also play key roles. One way that human activities could reduce future fire risk is by reducing fuel loads, particularly through restoration thinning and prescribed burning. In combination, these treatments can also provide ecological benefits including enhanced biodiversity, increased water availability, more sustainable carbon storage, improved forest resilience to climate change, and reduced air pollution.

Vegetation in California has changed dramatically over the last century due to direct changes in climate as well as indirect climate effects on disturbances such as wildfire and drought. The distribution of many Sierra Nevada vegetation types over the last century have shifted with yellow pine forests being replaced my more shade tolerant species largely due to fire suppression and not directly linked to changes in climate. However, subalpine forests have been affected by warming temperatures and steady precipitation which has reduced the stress leading to greater recruitment and survival in smaller size classes but higher mortality in larger trees. A profound effect over the last century was the 2012–2016 drought which initiated a severe tree mortality. Climate change effects on forests will be driven by the rate and magnitude of climate change, site specific conditions and the ability of species to shift distributions along with the effects of ecological stressors. While climate change plays out over long time periods, ecological stressors such as fire and drought can hasten these changes by triggering shifts in vegetation communities. Forested areas in the Sierra Nevada region are predicted to be 45% (hotter and wetter scenario) to 62% (hotter and drier scenario) highly climatically stressed under current emission levels (RCP8.5) by 2070-2099. Climate models suggest forest community composition in California in the late century may not change substantially, but community composition will be greatly simplified as the least tolerant species can no longer establish. Climate will indirectly enhance wildfire activity and drought intensity, which will both lead to changes in vegetation composition and structure. Moisture stress and the frequency and severity of bark beetle outbreaks are projected to increase dramatically with increasing temperatures in the Sierra Nevada, resulting in widespread tree mortality comparable to or greater than the 2012-2016 drought.

Climate change is impacting terrestrial wildlife species in a variety of ways across the Sierra Nevada, both directly and indirectly. Changes in climate can have direct physiological effects on species that may result in reductions in reproduction and survival causing future species range shifts across a species' distribution. These 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. Climate change can also lead to indirect impacts to wildlife by altering habitat, principally through climate's links to disturbances like fire. These impacts are explored using examples of wildlife species in the Sierra Nevada. Some examples explore impacts on broad taxonomic groups, such as small mammals and birds, while other examples focus on species of conservation or management concern. Key species include the California spotted owl (*Strix occidentalis occidentalis*), northern goshawk (*Accipiter*

gentilis), Pacific fisher (*Pekania pennanti*), Pacific marten (*Martes caurina*), and American pika (*Ochotona princeps*).

Contents

Historical Climate Trends

Methods for evaluating historical climate trends

Local trends in climate over the past century were summarized at the forest level from two local weather stations (WRCC 2006). 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 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.
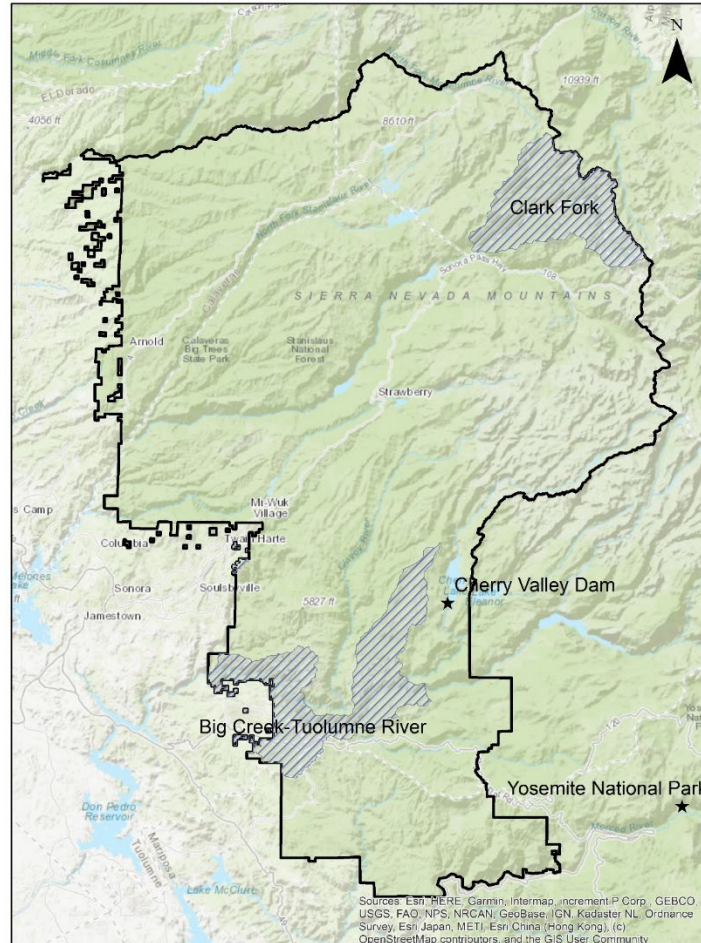

Figure 1. Location of local weather stations and watersheds (see future climate projections) evaluated for this report.

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)[1].

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	Number of missing WY	Calendar year (CY) record	Number of missing CY	Source
Cherry Valley Dam	4765	37^{0}58'29"	-119^{0}54'58"	1957-2020	9	1956-2019	3	WRCC
Yosemite National Park	3970	37^{0}45'00"	-119^{0}35'23"	1908-2018	35	1907-2019	10	WRCC
Stanislaus National Forest	1082-11528	-	-	1959-2018	0	1958-2019	0	Climate Engine

Temperature

Based on Terra Climate, the average minimum temperature has increased by 4.74°F across the Stanislaus National Forest since 1958. This trend is corroborated by statistically significant increases occurring at the Cherry Valley Dam (+8.60°F) and Yosemite National Park (+6.05°F) weather stations (Table 2, Figure 2). Increasing minimum temperatures have affected the number of months that have temperatures below freezing, which has decreased by 2-3 months (Table 2,

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[1] 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 et al. 2017).

Figure 2). Significant increases in average mean annual temperature have been recorded at the Cherry Valley Dam and Yosemite National Park weather stations (+3.14-5.17°F) (Table 2, Figure 2). Maximum temperature was stable (Table 2, Figure 2).

The increases in annual temperature on the Stanislaus National Forest are consistent with other climate analyses in California (e.g.Cordero et al. 2011), the Sierra Nevada (e.g. Gonzalez 2012), and at higher elevations in the region (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 in the last 37 years in California (Cordero et al. 2011). Rapacciuolo et al. (2014) report an average statewide temperature increase of 0.81°F between historic (1900-1939) and modern (1970-2009) times.

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

	Cherry Valley Dam	Yosemite National Park	Stanislaus National Forest (Terra Climate)
	1956-2019	1907-2019[1]	1958-2019
Mean Temperature (°F)	+5.17***	+3.14***	N/A
Max Temperature (°F)	ns	ns	ns
Min Temperature (°F)	+8.60***	+6.05***	+4.74***
Freezing (mo/yr)	-3.19***	-2.19***	N/A

[1]Missing data from: 2005-2010
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. Near significant trends are noted in parenthesis. Data gaps of more than 3 consecutive years are noted.

Precipitation
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 (Dettinger 2013). Over the period of record, there has been high variability in annual precipitation across the Stanislaus National Forest (Figure 3, Table 3).

Snowfall
Similar to variability in total precipitation, there has been a high degree of variability in total snowfall across the Stanislaus National Forest (Figure 4). Across the period of record there has been a significant decrease in total snowfall at the lowest elevation weather station (Yosemite National Park) (Figure 4, Table 3), however this station also has a high number of missing records, therefore this trend could be spurious (Table 1).
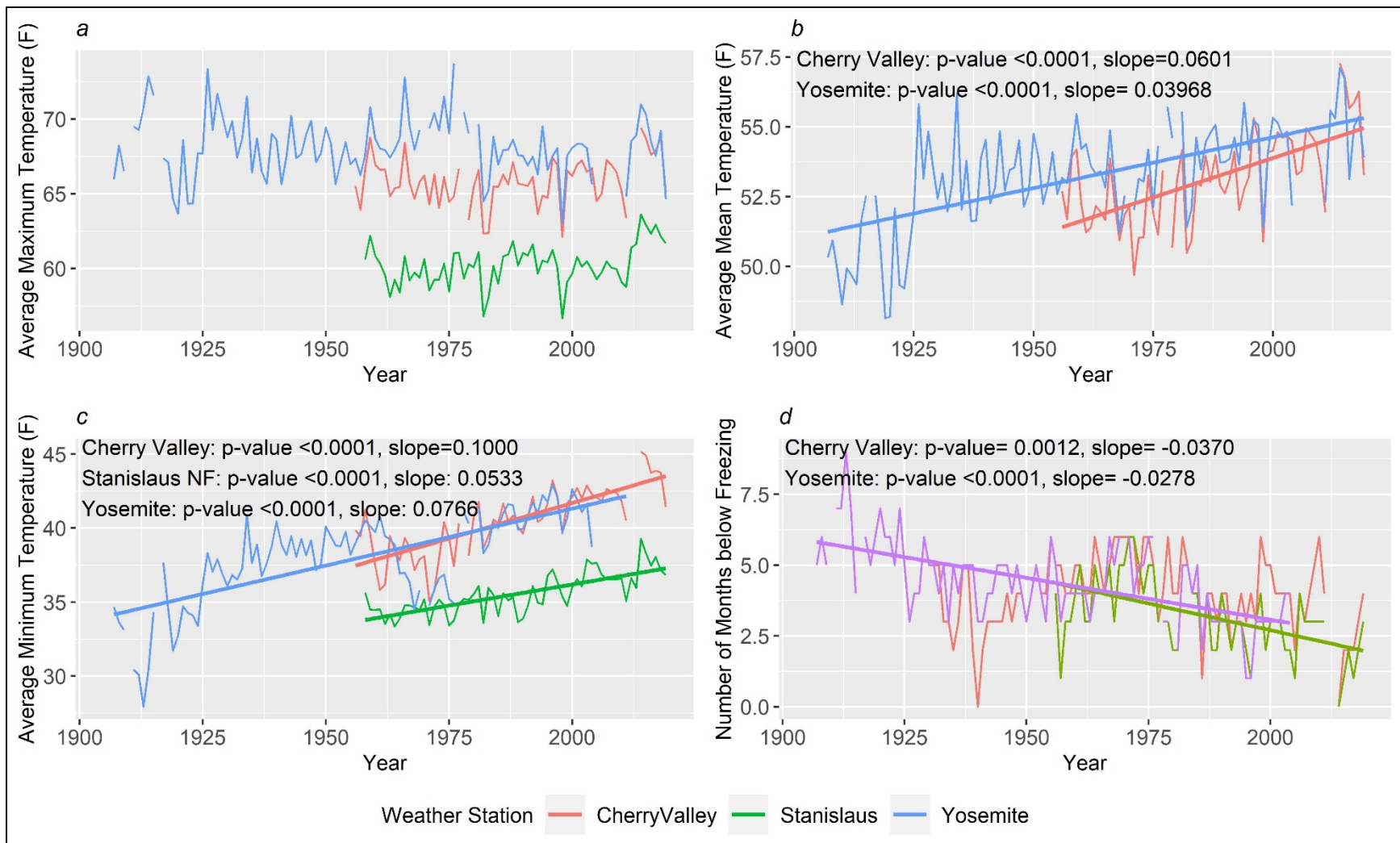
Figure 2. Historic temperature trends for Stanislaus National Forest weather stations (identified in different colors): a) Average Maximum Temperature, b) Average Mean Temperature, c) Average Minimum Temperature, and D) Number of Months below Freezing (months where the average minimum temperature was <32^{0}F). Linear lines indicate a significant trend. For all significant trends the level of significance (p-value) and magnitude and direction of trend (slope) are presented.
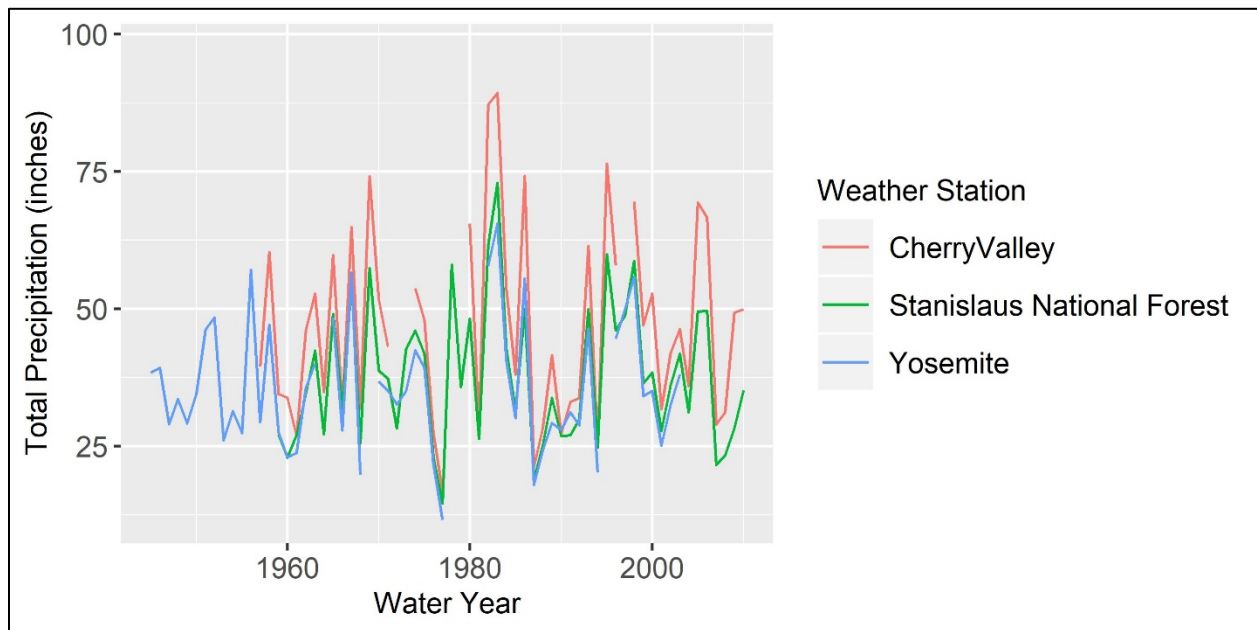
Figure 3. Total precipitation for local Stanislaus National Forest weather stations (identified in different colors).

While trends in total precipitation vary greatly across the western United States, some general changes in precipitation patterns have been observed since the mid-1900s. These shifts include: more rainfall and less snowfall (Knowles et al. 2006), decreased snow depth, particularly at low elevation sites (Mote et al. 2005, Barnett et al. 2008, Grundstein and Mote 2010), decreased snow water equivalent (SWE, a standard measure of the amount of water in snow) as proportion of precipitation (by 2-8% per decade) with the exception of high elevation areas like the southern Sierra Nevada (Mote et al. 2005, Barnett et al. 2008, Moser et al. 2009), and decreases in early spring (April 1) snowpack (Moser et al. 2009).

While trends in total snowfall were generally non-significant on the Stanislaus National Forest, a decline in snowfall across California has been documented. Precipitation falling as snow has declined and is 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). In the eastern Sierra Nevada, SWE has declined by 7% per decade from 1965 to 2018 (Biondi and Meko 2019). In the northern Sierra Nevada, between water years 1951-2017 the ratio of precipitation falling as snow significantly declined by 3.5% per year during water years 2008-2017 (Hatchett et al. 2017). In April 2015, measured Sierra Nevada snowpack was only 5% of its historical normal, and the next two lowest snowpack years were 2014 and 1977, when snowpack was 25% of normal (Dettinger et al. 2018). While these represent the general patterns, changes in snowfall vary by elevation. For example, while the northern Sierra Nevada shows a decrease in SWE since 1950, the southern Sierra Nevada actually shows a positive trend (Barnett et al. 2008, Christy and Hnilo 2010). This discrepancy is largely a result of the generally higher elevations in the southern Sierra Nevada, where cold areas with large increases in precipitation showed positive trends in SWE from 1950 to 1997 (Mote et al. 2005).

In California, the decline in the snow to rain ratio has been linked to atmospheric rivers (Hatchett et al. 2017). An atmospheric river has been called a "river in the sky" where strong water vapor is linked to tropical or extratropical moisture source that frequently leads to heavy precipitation (Ralph 2018). 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).
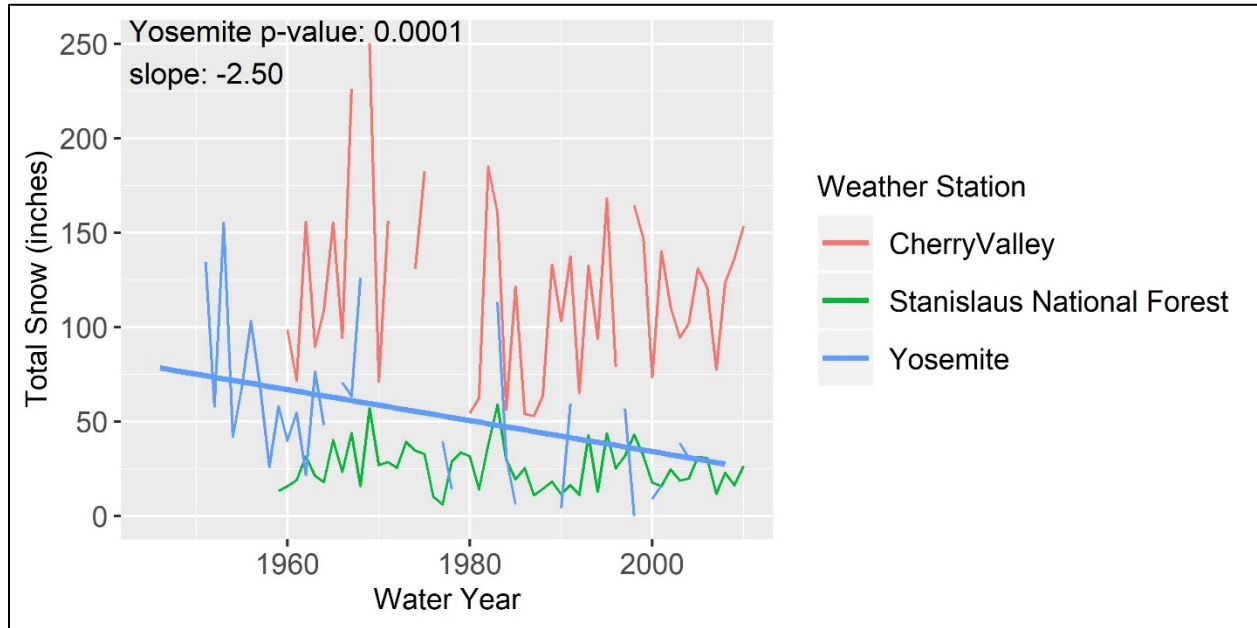
Figure 4. Total snowfall for local Stanislaus National Forest weather stations (identified in different colors). Linear lines indicate a significant trend. For all significant trends the level of significance (p-value) and magnitude and direction of trend (slope) are presented. *Note that data for the Stanislaus National Forest (Terra Climate) are Snow Water Equivalent (in inches), while data for the individual weather stations are Total Snow (in inches).

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

	Cherry Valley Dam[1]	Yosemite National Park[2]	Stanislaus National Forest (Terra Climate)
	1957-2020	1908-2018	1959-2018
Total Precipitation (in.)	ns	ns	ns
Coefficient of variation	ns	ns	ns
Snowfall (in.)	ns	-135***	ns

[1]Missing: 2011-2013; [2]Missing: 1916-1926, 1978-1981, 2004-2011, 2013-2015

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.

Drought

The recent California drought (2012-2016) was arguably the most severe of the last millennium (Griffin and Anchukaitis 2014, Mann and Gleick 2015). The drought occurred due to low precipitation combined with record high temperatures (Griffin and Anchukaitis 2014). The event greatly reduced mountain snowpack, and spring runoff (DWR 2014, U.S. Geologic Survey 2014, Monitor 2020). The 2015 April SWE was so low that Belmecheri et al. (2016) estimated that this was a one-in-3100 year event. In 2015, there was a multi-year (2012-2015) snow water equivalent deficit of approximately 5 trillion gallons of water (-1.78×10^7 acre feet) in the Sierra Nevada (Margulis et al. 2016), which is equal to 13.5% of the capacity of Lake Tahoe. Given the prediction of more extreme and prolonged drought events (Berg and Hall 2017), the effects observed in this last drought likely portend common conditions in the future (Diffenbaugh et al. 2015). In the eastern Sierra Nevada, droughts have shifted between longer (4-year) periods of drought and periods of wetness, thus increasing the interannual variability in this region (Biondi and Meko 2019).

Historical Hydrology Trends

Sierra Nevada snowmelt contributes a huge proportion of water to California agricultural and public supplies and is very vulnerable to climate-related hydrological changes. Changing hydrology in the Sierra Nevada is influencing forests, wildfire, wildlife and public health. Generally, over the last 50 years, less precipitation is falling as snow and the reduced snowpack is melting earlier, resulting in snow drought (Howat and Tulaczyk 2005, Mote et al. 2005, Stewart et al. 2005, Mote 2006, Mote et al. 2016, Safeeq et al. 2016). Underlying these general trends, the range of hydrologic responses to climate change in the Sierra Nevada is influenced by geography and elevation. Null et al. (2010) assessed the vulnerability to climate warming of 15 west-slope watersheds in terms of changing hydrology in the Sierra Nevada and found differing vulnerabilities for different segments of the mountain range. They found that mid- and high-elevation watersheds in the south-central Sierra Nevada were most likely to exhibit earlier runoff, while watersheds in the northern Sierra Nevada were most likely to show the greatest reductions in mean annual flow, and central Sierra Nevada watersheds were most likely to experience extended periods of low flow conditions (Null et al. 2010).

Snowpack Drought

Snow drought has been linked to extreme early season precipitation, frequent rain on snow events and low precipitation years (Hatchett and McEvoy 2017). Snow drought results in lower stream flows throughout the dry season (Godsey et al. 2014) and warming trends in high elevation Sierra Nevada lakes (Sadro et al. 2019).

Snowmelt Timing/Peak Runoff

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. Over the last half-century, peak runoff and streamflow has shifted earlier in the year for many Sierra Nevada watersheds due to earlier snowmelt timing (Regonda et al. 2005, Stewart et al. 2005, McCabe et al. 2007, Young et al. 2009, Hatchett and McEvoy 2017). Snowmelt now occurs about 10-15 days earlier on average compared to the early 1900s (Baldwin et al. 2003). Over a 55-year period ending in 2002 spring thaw occurred 5-20 days earlier on the western slopes of the Sierra Nevada, and peak streamflow occurred 0-15 days

earlier during that time (Stewart et al. 2005). When more streamflow occurs earlier in the season, later months experience significantly less streamflow. March flows in Sierra Nevada streams were significantly higher by 3-10%, whereas June flows were mostly lower by the same amount, and overall spring and early summer streamflow was down in most streams (Stewart et al. 2005). The April-July component of annual runoff has decreased by 23% in the Sacramento basin and by 19% in the San Joaquin basin in California over the last century (Moser et al. 2009). 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).

Streamflow volume
Streamflow volume is connected to precipitation patterns and runoff timing and has important consequences for aquatic fauna, wildlife and forest plants. Streamflow in the Feather River, one of the largest streams in northern California, has been reduced by a sum total of 400,000 acre feet over 60 years (1950 – 2010) (Dettinger et al. 2018). Most other rivers in California have experienced similar declines in total streamflow. In addition to the long-term decline in streamflow, California has also experienced one of the greatest increases in variability in streamflow volume in the western U.S. since the 1980s (Pagano and Garen 2005).

The 2012-2016 California Drought
The recent California drought (2012-2016) brought very low winter precipitation, mountain snowpack, and spring runoff (Heim 2020),which in combination reduced streamflow, runoff, and ground-water recharge. Reduced precipitation at lower elevations (1968-6561 ft) during the drought resulted in more water being removed from groundwater storage through plant evapotranspiration than could be recharged through precipitation (Bales et al. 2018). This four-year moisture overdraft, wherein evapotranspiration exceeded precipitation by ~60 in and exhausted subsurface moisture to 16-49 ft depth, is linked to widespread tree die-off in the lower mixed conifer forests of the southern Sierra Nevada (Goulden and Bales 2019). Belowground moisture typically buffers streamflow and reduces drought impacts on deeply rooted Sierra Nevada conifers (Jepsen et al. 2016), but the prolonged 2012-2016 drought depleted root-accessible moisture. While impacts of the drought on mountain runoff in the southern Sierra Nevada were exacerbated by a 1.8°F increase in temperature relative to the previous decade, they were mitigated by wildfire and drought-associated tree mortality. After tree and understory mortality had occurred, total evapotranspiration lessened, thus leaving more water available for runoff (Bales et al. 2018).

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 time frames, 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

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for the western US in the 20th century, where climate has been a strong driver of fire size, frequency and severity (Westerling et al. 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 different 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.

Historical Fire Trends

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 et al. 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). Miller et al. (2009) showed that fire size and total area burned had increased in the Sierra Nevada since the mid-1980s. Additionally, the number of large fires (≥1000) acres significantly increased between 1950 and 2010 in the Sierra Nevada (Miller and Safford 2012). Westerling (2016) found that the area burned in the Sierra Nevada between 2002-2012 had increased by 324% compared with 1973-1982. Williams et al. (2019) reported that annual area burned across the Sierra Nevada had increased by 405% between 1972 and 2018. Wildfires have also been occurring at higher elevations in the Sierra Nevada over the past century (Schwartz et al. 2015). Mallek et al. (2013) showed that relative increases in annual area burned between 1984 and 2010 were greatest in Sierra Nevada subalpine communities.

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). Miller et al. (2009) showed that forest fire severity rose steeply in the Sierra Nevada between 1984 and 2007, particularly in middle elevation conifer forests. Miller et al. (2009) found that in 1984 fires burned at an average of about 17% high severity, while the average between 1996 and 2006 was 30%.

Effects of temperature on fire activity

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 related to dry, warm conditions during the fire season (Littell et al. 2009, Spracklen et al. 2009, Westerling 2016). Although average annual precipitation in California and the Sierra Nevada 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). Little et al. (2009) found that in the Sierra Nevada high temperatures, low precipitation, and drought immediately prior to and during the fire season most strongly affected fire activity.

Effects of precipitation and snow cover on fire activity

Although precipitation amounts have not changed over the past century in the Sierra Nevada, precipitation patterns still 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. Littell et al. (2009) found that the model that best explained the increase in area burned in the Sierra 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 et al. 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).

Significant declines in snow cover over the past century has also affected fire activity by moderating lightning and therefore the potential for lightning-caused fires. High levels of snowpack keep surface temperatures low, decreasing the convective forces necessary for lightning. Lutz et al. (2009b) found that high levels of spring SWE were associated with decreased lightning strikes, decreased numbers of lightning-ignited fires, and reduced area burned between 1984 and 2005 in Yosemite National Park.

Effects of fuel aridity on fire activity

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 5). 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. Williams et al. (2019) found that the positive correlation between fire activity and fuel aridity was stronger in the Sierra Nevada than in most other areas of California.
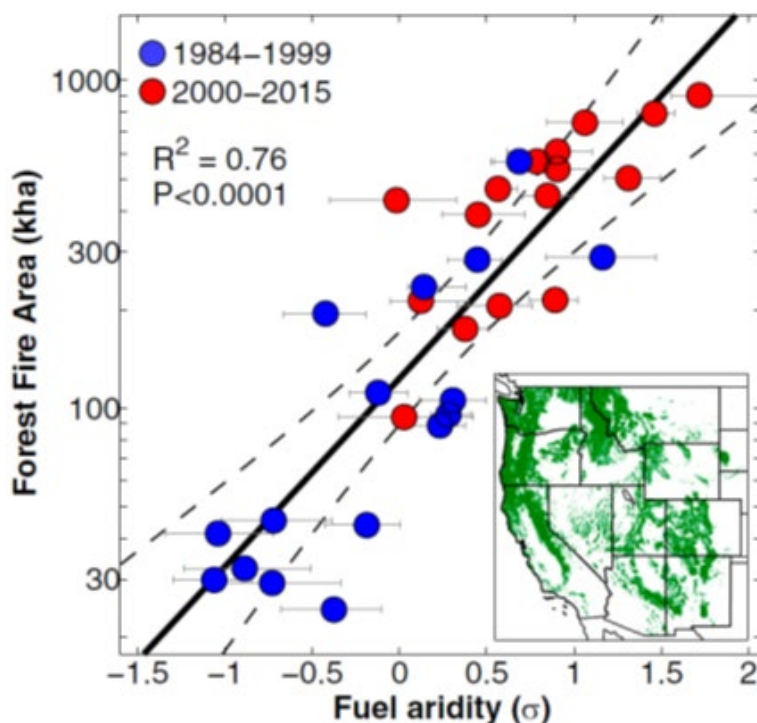
Figure 5. Annual western US forest fire area versus fuel aridity from 1984-2015. From (Abatzoglou and Williams 2016).

Effects of fire season length on 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 et al. (2006) found that increasing frequencies of large fires (>1000 acres) across the western US since the 1980's were strongly linked to increasing temperatures and earlier spring snowmelt. 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. This effect was particularly evident in mid-elevation forests of the Sierra Nevada. Abatzoglou and Williams (2016) estimate that 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.

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 dramatically 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.

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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 currently and in the future (Thorne et al. 2017).

Distribution of Vegetation

The distribution of many Sierra Nevada vegetation types over the last century has shifted (Figure 6) (Thorne et al. 2008, McIntyre et al. 2015). The main distributional changes in lower elevation foothill communities are transitions to grassland from blue oak woodland and shifts from chaparral to hardwood exacerbated by land use changes (Thorne et al. 2008). Yellow pine dominated forests have mostly been replaced by mixed conifer due to the suppression of fire (and selective cutting of yellow pines and sugar pine) and in some cases by montane hardwoods. Mixed conifer vegetation types have also exhibited shifts from more shade-intolerant pines to more shade-tolerant conifers (Thorne et al. 2008, Dolanc et al. 2014a, Dolanc et al. 2014b). Although these trends might be driven by climate warming and reductions in precipitation, human management choices, including logging, fire exclusion, and urban expansion have also heavily influenced vegetation distribution, particularly in the lower elevation montane hardwood and mixed conifer forests (Thorne et al. 2008, McIntyre et al. 2015). Alpine and subalpine communities have also seen a reduction in distribution (Thorne et al. 2008). Recruitment in subalpine species has shifted upwards in elevation in the Sierra Nevada pushing subalpine trees into previous permanent snowfields (Dolanc et al. 2013, Wright et al. 2016).

Structure and Composition of Low Elevation Forests

Low elevation west slope forest types such as montane hardwood and mixed conifer forests, have been the most impacted by human management choices, such as fire exclusion (Dolanc et al. 2014b, Barth et al. 2015). However, climate is also a contributing factor to changes in composition in lower elevation forests. Increased abundance of evergreen oaks in the foothill oak forest types and a shift in dominance from pines to oaks in montane hardwood communities are consistent with evidence of water stress and increased pressure from disturbances (Dolanc et al. 2014b). Oaks have certain traits that make them better adapted to the consequences of climate change such as drought tolerance and ability to resprout following disturbances. Another change in composition includes a shift to more shade-tolerant conifers, though this is not clearly tied to a climate signal but is rather a consequence of past management activity (chiefly fire suppression and logging) that has negatively impacted shade intolerant/fire tolerant species like the pines (Dolanc et al. 2014a).

Few individual tree or plant species studies exist detailing the direct effects of climate over the last century. Johnson et al. (2017) looked at climate changes on tree species in the Sierra Nevada. All species benefited from milder winter conditions with increases in growth. Seedling survival and growth has also been impacted by climate changes. Higher July maximum temperatures
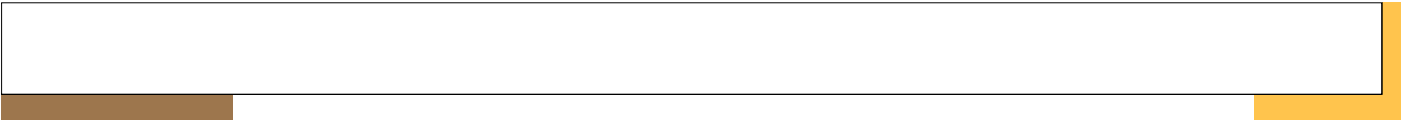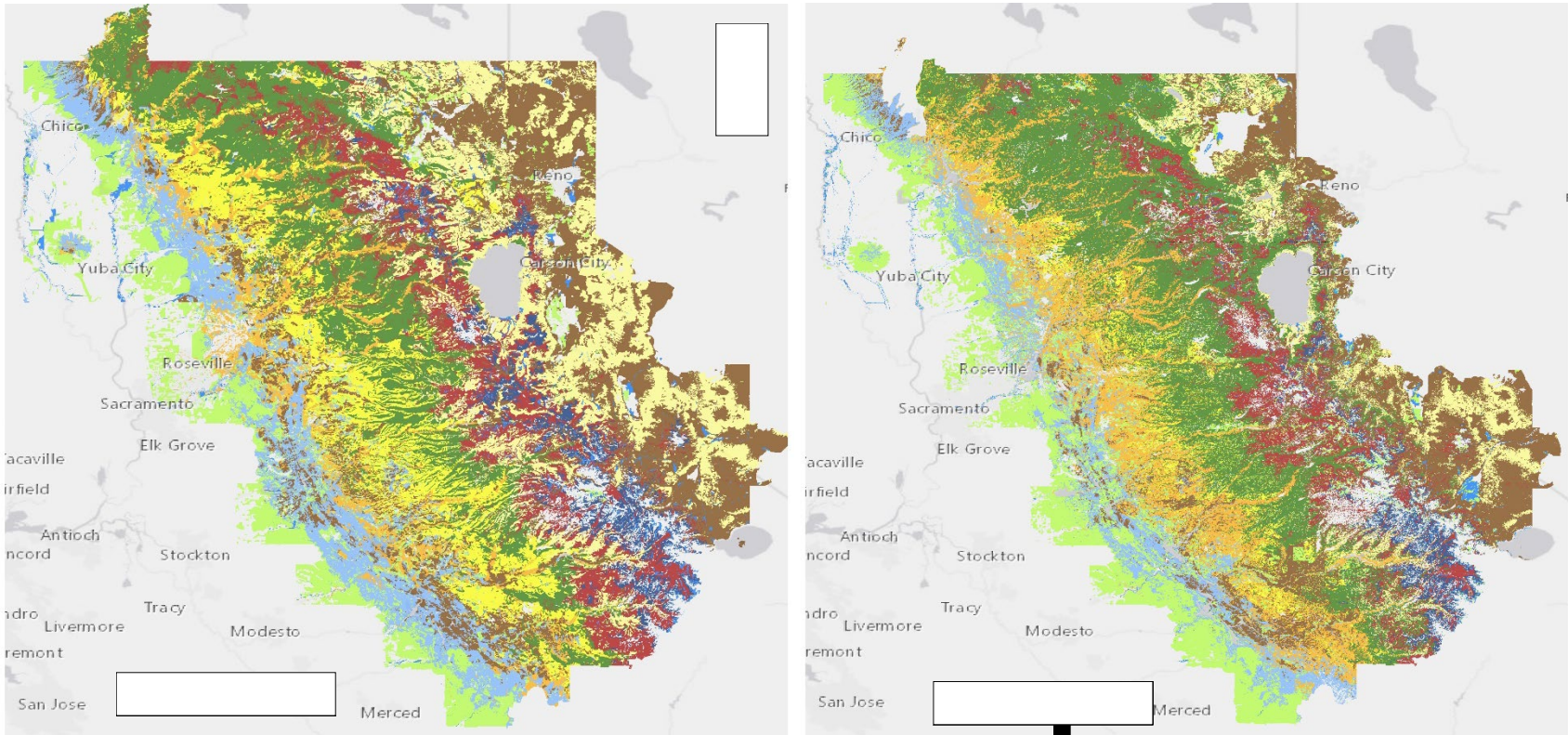
Figure 6. The distribution of major vegetation types in the Sierra Nevada in the period from 1932-1936 as mapped by Wieslander (left panel) compared to current conditions (right panel).

were associated with lower survival and growth while higher precipitation had a positive effect on survival but negatively affected growth (Slack et al. 2017, Moran et al. 2019). Certain species such as *Quercus chrysolepis* and *Calocedrus decurrens*, which have both increased in abundance, appear to be well positioned to do quite well in the future (Dolanc et al. 2014a).

Tree density is significantly higher in almost all of the west slope vegetation types as compared to conditions a century ago (Dolanc et al. 2014a, Dolanc et al. 2014b, McIntyre et al. 2015). The increase is skewed towards smaller fir trees (Dolanc et al. 2014b) (Figure 7) as recruitment and growth of shade-tolerant species has improved, shifting mixed conifer stands to more dense fir- and incense cedar-dominated stands (Levine et al. 2016, Moran et al. 2019). These changes may not be linked to climate as mentioned above but have certainly made forests more susceptible to water 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 climate- and stand density-driven water stress, but also logging in some areas (Dolanc et al. 2014b, Easterday et al. 2018) (Figure 8).
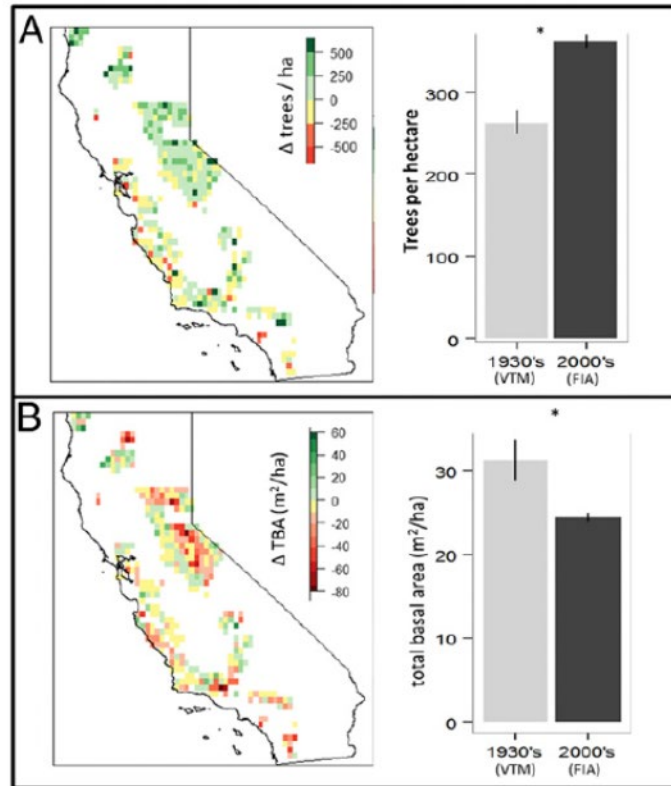

Figure 7. Changes in tree density per hectare (for all size classes) (A) and average basal area (B) between Wieslander (VTM) and existing conditions (FIA) (McIntyre et al. 2015).
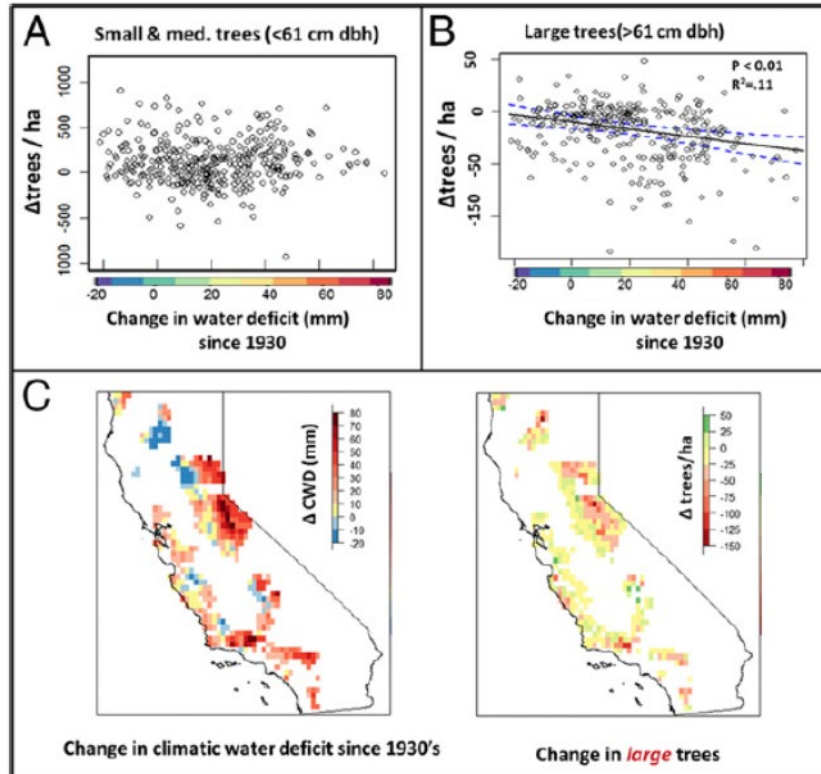
Figure 8. Changes in tree density and climatic water deficit between Wieslander and existing conditions for small & medium trees (A&C) and large trees (B&C) (McIntyre et al. 2015).

Structure and Composition of High Elevation Forests

Compositional changes in higher elevation and east slope vegetation types have largely been shifts to shade-tolerant species and increases in the hardwood component (Dolanc et al. 2013). Subalpine forests have also been affected by warming temperatures and steady or increasing precipitation which has reduced stress, leading to greater recruitment and survival in smaller size classes but higher mortality in larger trees (Dolanc et al. 2013). Tree density increased in subalpine communities (Dolanc et al. 2013). This increase, largely driven by small stems, is a direct result of changing climatic conditions (Dolanc et al. 2013).

The 2012-2016 California Drought

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 (Paz-Kagan et al. 2017, Preisler et al. 2017, Young et al. 2017, Fettig et al. 2019). Mortality on the Stanislaus National Forest as recorded by Forest Service Aerial Detection Surveys provides evidence of the dramatic changes to the forested landscape (Figure 9) (U.S. Forest Service 2016). During this drought period, tree mortality increased from an estimated 129 million trees dying across the state (Young et al. 2017, Young et al. 2019). 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. 2019). 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) 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 changed substantially in the Sierra Nevada in response to the 2012-2016 drought event. 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). 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. 2019) .

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, gray pine (foothill zone), Jeffrey pine, and lodgepole pine (upper montane zone). Relatively lower levels of mortality occurred in oaks (with some localized areas of higher blue oak mortality in the foothill zone), and the lowest mortality levels were observed in giant sequoia and subalpine conifers such as whitebark pine and foxtail pine (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. 2019, 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).

Stanislaus NationalForest

Tree Mortality 2012-2016
Dead Trees per Acre

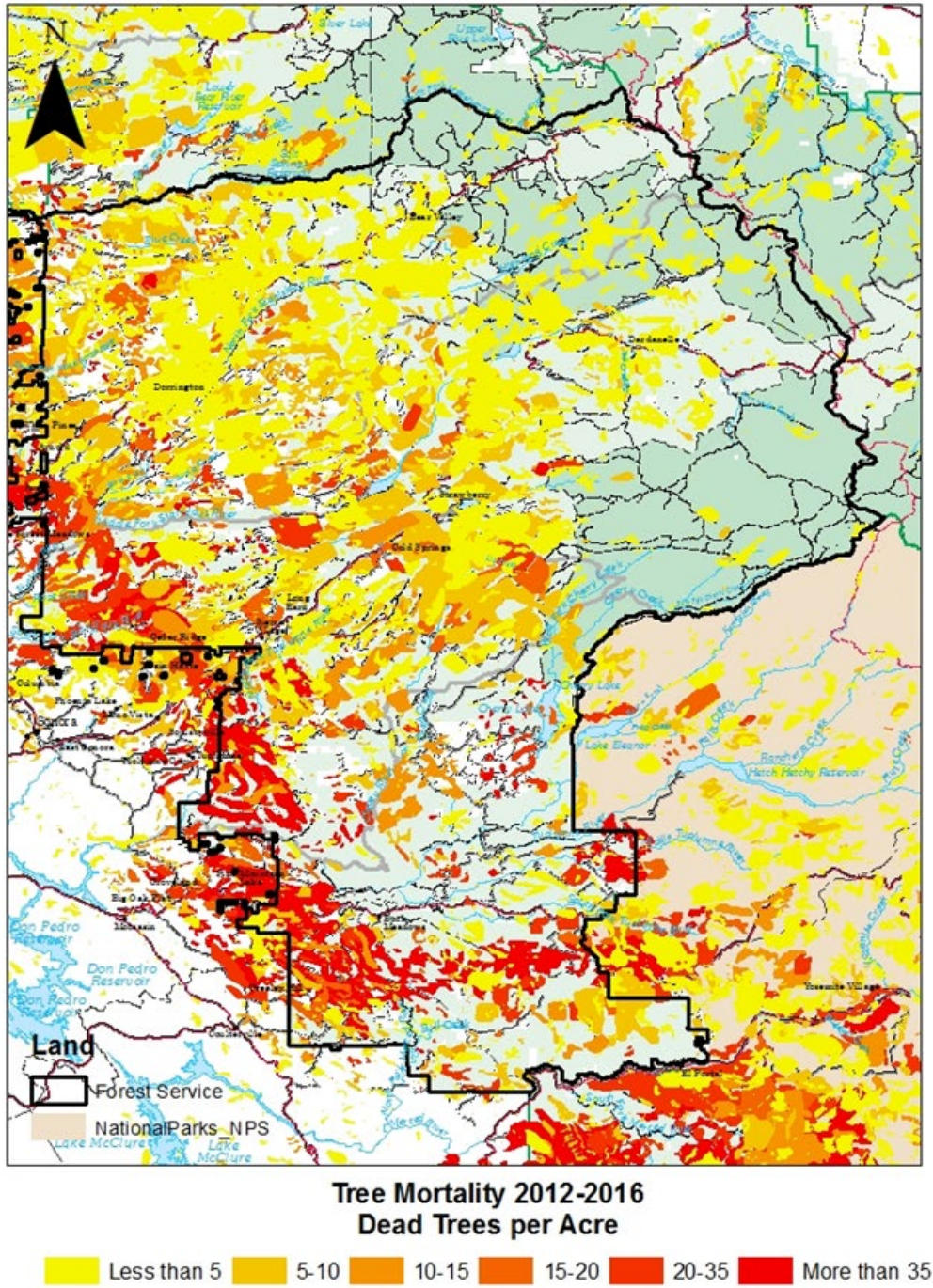Less than 5   5-10   10-15   15-20   20-35   More than 35

Figure 9. Recent (2012-2016) cumulative drought and insect-related mortality in the Stanislaus National Forest based on aerial detection surveys by the drought. Forest Service Forest Health Protection.

Historical Meadow Vulnerability

Meadows rely on surface and subsurface soil moisture to persist and are therefore vulnerable to changes in both temperature and precipitation. In the Sierra Nevada, the area occupied by five fens (groundwater dependent wet meadows) declined by 10-16% over 50-80 years, while in the Cascade range there were no discernable changes in a set of studied fens due to a combination of more mild changes in climate and hydrogeological differences (Drexler et al. 2013). Meadow vegetation in the Sierra Nevada is very sensitive to changes in April 1st snowpack, particularly alpine and subalpine meadows with high average precipitation and limited catchment subsurface storage (Albano et al. 2019). We used the Sierra Nevada Meadow Climate Vulnerability assessment dataset to identify meadows on the Stanislaus National Forest that are sensitive to changes in April 1st snowpack (Albano et al. 2019, Gross et al. 2019). This dataset defines sensitivity as the slope of the relationship between April 1st snowpack and late season greenness (Normalized Difference Vegetation Index-NDVI). Meadows that are most sensitive are meadows where late season vegetation phenology is synchronized closely with April 1st snowpack. These meadows have a strong dependence on water sources derived from snow melt. Sensitivity scores are only available for larger meadows due to Landsat image pixel size (Albano et al. 2019). On the Stanislaus National Forest between 1984 to 2016, meadow vegetation as measured by NDVI, suggested that 66% of the meadows were sensitive to changes in April 1st snowpack (38% showing a high sensitivity and 28% showing a medium sensitivity) (Figure 10) (Gross et al. 2019).

Historical Wildlife Trends

Climate change is impacting terrestrial wildlife species in a variety of ways across the Sierra Nevada, both directly and indirectly. 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 historic 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).

These 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 the Sierra Nevada 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).
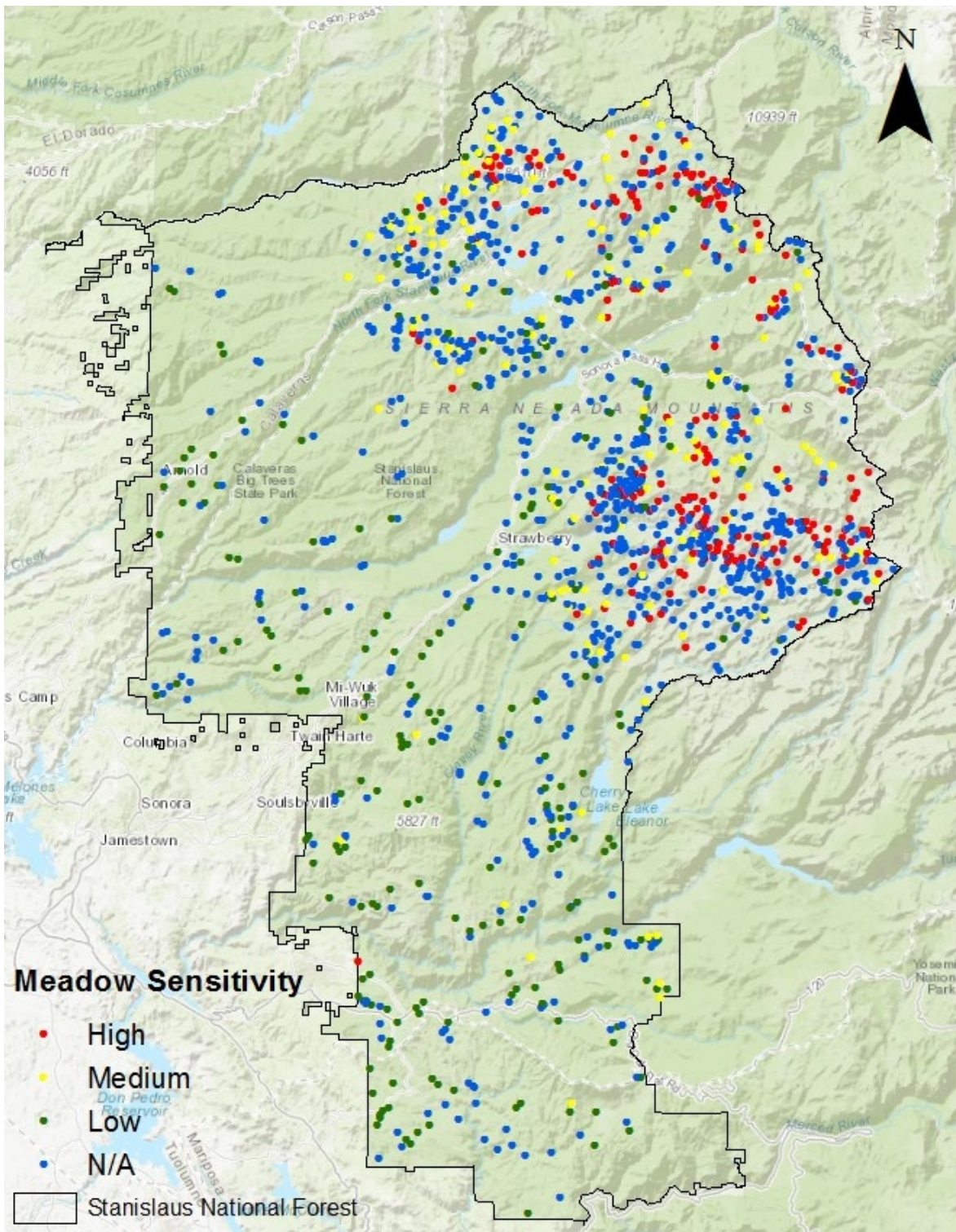
Figure 10. Meadow sensitivity on the Stanislaus National Forest based on the slope of the relationship between April 1st snowpack and late season greenness (Normalized Difference Vegetation Index-NDVI) between 1984 to 2016.

to climate change than other species and may be especially prone to move as climates warm (Jiguet et al. 2006, Gardali et al. 2012).

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Due to varying life history traits, physiological characteristics, and habitat requirements, species show differing degrees of vulnerability and adaptability to changes in climate. This section uses examples of wildlife species in the Sierra Nevada to explore some of the direct and indirect climate change impacts introduced above. Some examples explore impacts on broad taxonomic groups, such as small mammals and birds, while other examples focus on species of conservation or management concern. Key species include the California spotted owl (*Strix occidentalis occidentalis*), northern goshawk (*Accipiter gentilis*), Pacific fisher (*Pekania pennanti*), Pacific marten (*Martes caurina*), and American pika (*Ochotona princeps*).

Direct Impacts

Physiological effects and Range Shifts

Though difficult to detect, direct effects of climate change have been hypothesized for multiple species in the Sierra Nevada, particularly old growth specialists of concern, like California spotted owls and Pacific fishers. In some parts of the spotted owl's range, drought and high temperatures during the previous summer have been linked to lower survival and recruitment the following year (Franklin et al. 2000, Glenn et al. 2011, Jones et al. 2016b). Jones et al. (2016b) note that an increase in summer temperatures from 1993 to 2012 occurred concurrently with declines in spotted owl occupancy in their study area over the same time period. However, these declines in survival and recruitment may be linked to changes in prey populations rather than direct physiological impacts, as discussed later.

Conversely, northern goshawk (*Accipiter gentilis*) has exhibited positive responses to higher-than-average late-winter and early-spring temperatures (Keane et al. 2006). This study found that northern goshawk reproduction was 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).

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). Within their home ranges, fishers select resting sites that have lower heat load indices relative to available sites (Aubry et al. 2013) and dens tend to be in areas with relatively low summer temperatures (Spencer et al. 2015b). However, Zielinski et al. (2017)

found that fishers do not occur where snowpack depth is greater than 25.6 inches (in), and most fishers were detected in sites where snow depth was less than 23.5 in.

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 in of annual precipitation and the majority were detected at sites that received at least 40.9 in 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 Sierra Nevada 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, (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). Analogous resurvey efforts along two other Sierra Nevada transects showed equivalent elevational shifts for 22 out of 34 small mammals, with other species showing heterogeneous range shifts over the past century (Rowe et al. 2015).

Similar distributional changes have been observed for other faunal taxa throughout the Sierra Nevada. Forister et al. (2010) tracked 159 species of butterflies over 35 years in the central Sierra Nevada and observed upward shifts in the elevational range of species, a pattern consistent with a warming climate. Tingley et al. (2009) resurveyed bird distributions along the three Sierra Nevada Grinnell transects and concluded that 91% of species shifted ranges to track their climate niche. Tingley et al. (2012) surveyed more bird species across a broader geographic area and found that 84% of species shifted their range with changes in temperature and precipitation, though shifts were not always upslope. Despite these high rates of climate sensitivity, only 51% of these species saw upslope shifts in range boundaries, likely attributable to conflicting directional pressures of changes in temperature and precipitation as well as inconsistent precipitation changes along elevational gradients over the last century (Tingley et al. 2012).

An alternate response to warming spring trends is 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.

Indirect Impacts

Alterations to community dynamics

Shifting species' distributions in response to climate change can create novel species assemblages, in turn leading to new competition and/or predation pressures, alterations in prey availability, or shifting disease and parasitism dynamics (Stralberg et al. 2009). While species exhibiting range contraction or upslope shifts are likely limited by thermal tolerance and contraction of suitable habitat (e.g. alpine chipmunk, *Tamias alpinus* and Sonoma chipmunk*, T. 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 particular species and assemblages (Beever et al. 2011).

In addition to direct climate sensitivity, wildlife may 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 and associated moisture stress may reduce production of plants, seeds, and fungi that are important food for spotted owl prey species, such as wood rats and flying squirrels (Seamans et al. 2002, Olson et al. 2004, Glenn et al. 2010, Glenn et al. 2011). Jones et al. (2016b) suggest that the higher 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).

Changes in habitat quantity, quality, and distribution

Alterations to habitat are another indirect climate impact on wildlife species. Climate change over the last century has affected wildlife habitat in the Sierra Nevada both directly (e.g. through moisture-stress induced mortality of trees) and indirectly (e.g. through loss of habitat to severe fire). While upwards range shifts for high-elevation small mammal species are consistent with

predicted climate warming, changes in most 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).

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 the Sierra Nevada, 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)).

The same tree mortality event had negative impacts on bird populations in the Sierra Nevada, negating some of the productivity benefits of warmer, drier springs (Roberts et al. 2019). Tingley et al. (2020) examined the impacts of the 2012-2016 drought on black-backed woodpecker occupancy and found that occupancy of the snag dependent species was more than 12 times lower in beetle-killed stands than fire-killed stands in the Sierra Nevada. The authors suggest that this is likely due to lower food resource availability in beetle-killed than fire-killed snags, at least in areas of high burn severity (Ray et al. 2019, Tingley et al. 2020).

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, basal area, and shrub cover 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 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 spotted owl 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 owl extinction probability (Lee et al. 2013) over the last two decades. Where greater than half of an owl territory burned at high-severity in the 2014 King Fire, 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 owl 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).

Even some severe-fire dependent species may be negatively impacted by the increasing sizes of high-severity fire patches. Stillman (2019) suggest that the increasing prevalence of large, homogenous high-severity 'megafires' is an emerging threat even to post-fire specialists. Tingley et al. (2018) found that black-backed woodpecker colonization declined with fire size, Stillman et al. (2019) found that black-backed woodpeckers selected nest sites relatively close to (within

0.3 miles) low-severity or unburned edges, and Stillman et al. (2019) noted the importance of pyrodiverse areas in supporting black-backed woodpeckers through their multiple life-history stages. Alternatively, moderate- to high-severity fires may improve accessibility of foraging habitat and increase habitat heterogeneity for other species, as seen in burned areas in the Sierra Nevada that had increased species richness and occupancy rates of bats during 2014-2017 (Steel et al. 2019).

Future Climate Predictions

Methods for evaluating future climate predictions

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 global climate models (GCMs) to project future climate conditions. 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), MIROC5 (most unlike any other model). 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 11). 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).
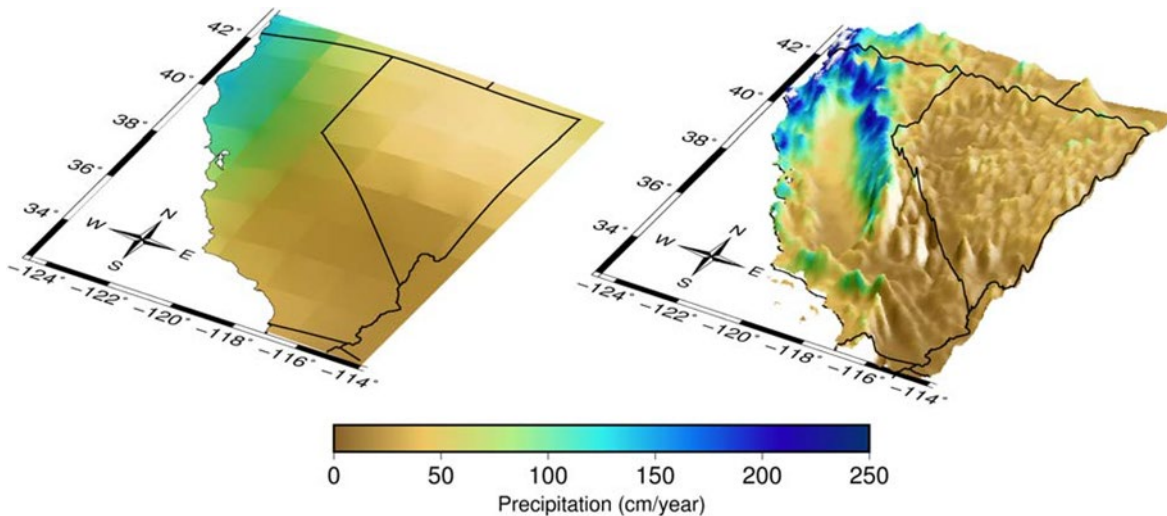
Figure 11. Annual precipitation in California and Nevada (250 cm = ~100 inches). On the left is a global climate model with a resolution of 100 miles. On the right, downscaled model with a resolution of about 3.7 miles. Note how the downscaled model is better able to better capture the wet conditions on the west slope and drier conditions on the east slope of the Sierra Nevada. Image was taken from (Pierce et al. 2018) where the vertical scale has been equally exaggerated in both images for clarity.

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 Stanislaus National Forest based on an average of the four priority models identified for California. When summary data were not available for the forest, data were summarized for the Big Creek-Tuolumne River Watershed and the Clark Fork Watershed. 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.

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. In 2021-2022, IPCC will come out with their 6th assessment, which will use CMIP6 and an extended set of RCP scenarios paired with shared socioeconomic pathway (SSP) to better describe future socioeconomic, demographic, and technological trends (https://www.carbonbrief.org/timeline-history-climate-modelling). While climate modeling has evolved, older literature with previous GCM/CMIP and emission scenarios can still provide insight into future changes in climate.

Temperature

Similar to historical trends, average temperature is predicted to increase under both RCP 4.5 and 8.5 scenarios (Table 4, Figure 12). Annual average maximum temperatures are projected to increase by 1.0°F to 3.3°F in the early part of the century (2010-2039) and by 6.0°F to 10.5°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 2.2°F to 4.3°F in the early part of the century (2010-2039) and by 7.3°F to 11.3°F by the end of the century (2070-2099) (Table 4). At the Supervisors Office in Sonora, CA average minimum December and January temperatures will be comparable to current average minimum April and October temperatures by the end of the century. In addition, the projected average maximum temperature in July and August in Sonora will equate to current temperatures in Joshua Tree, CA or Las Vegas, NV.

Table 4. Modeled historic and future average minimum and maximum temperature on the Stanislaus National Forest summarized for 30-year periods for emission scenarios RCP 4.5 and 8.5. Projected future change compared to modeled historic (1950-1979) temperatures 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 (in °F)	Min.	57.5	56.8	60.6 (+3.1)	58.5 (+1)	61 (+3.5)	61 (+3.5)	63.5 (+6)	63.5 (+6)
	Ave.	60.4	61.1	63.4 (+3)	63.7 (+3.3)	65 (+4.6)	66.3 (+5.9)	66.8 (+6.4)	69.9 (+9.5)
	Max.	63.6	64.4	66.7 (+3.1)	66.9 (+3.3)	68.9 (+5.3)	71.6 (+8)	70.7 (+7.1)	74.1 (+10.5)
Annual Average Minimum Temperature (in °F)	Min.	31.9	32.9	34.4 (+2.5)	34.1 (+2.2)	36 (+4.1)	36 (+4.1)	36.4 (+4.5)	39.2 (+7.3)
	Ave.	33.9	34.7	36.8 (+2.9)	37.1 (+3.2)	38.4 (+4.5)	39.8 (+5.9)	39.6 (+5.7)	43.2 (+9.3)
	Max.	36.1	38	40.7 (+4.6)	40.4 (+4.3)	41.4 (+5.3)	43.4 (+7.3)	42.1 (+6)	47.4 (+11.3)

Modeled temperature data was collected from CalAdapt and is 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.
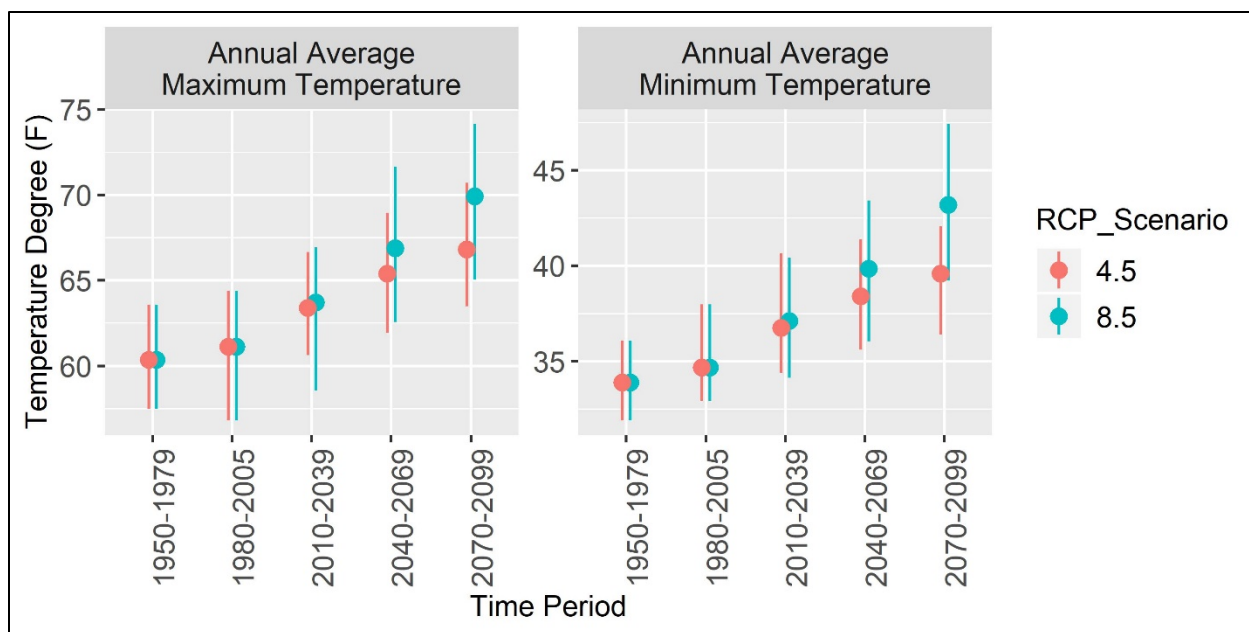
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Figure 12. Modeled historic and future average minimum and maximum temperature on the Stanislaus National Forest summarized for 30-year periods. Points represent average while lines indicate range of data (minimum and maximum). Data source CalAdapt: See Table 4 footnote.

Increasing temperatures result in a greater number of days and nights above freezing (Figure 13). The magnitude of these changes is greater in the upper elevation watershed (Clark Fork Watershed). By the end of the century, in the upper elevation watershed (Clark Fork Watershed), where freezing temperatures are even more critical to maintain snow pack, the average number of nights above freezing increases by 72 days (116 to 188 days), while the average number of days above freezing increases by 68 days (288 to 356 days). By the end of the century, in the lower elevation watershed (Big Creek-Tuolumne River Watershed), the average number of nights above freezing increases by 63 days (268 to 331 days). Historically in the lower elevation watershed, there are no days below freezing therefore this will not change.

The increases in predicted future temperature on the Stanislaus 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. In the Sierra Nevada, the average elevation of the freezing line will rise from 4920 to 7380 feet by the end of the century (Rhoades et al. 2018b).
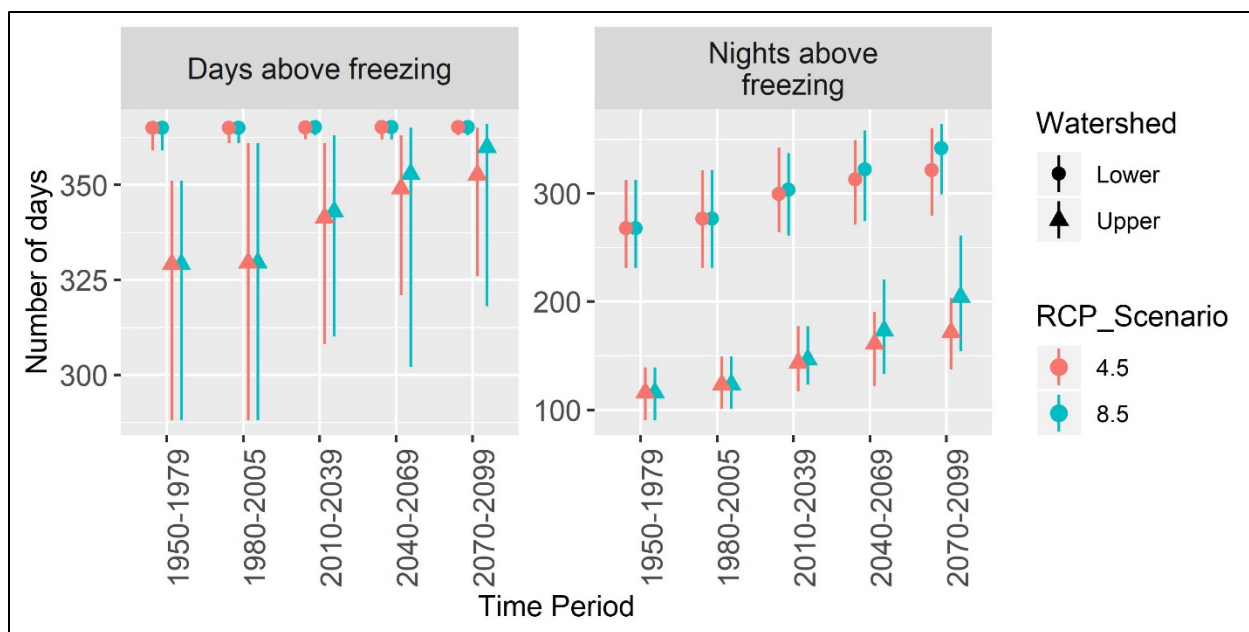
Figure 13. Modeled number of days above freezing (32°F) for the Clark Fork Watershed and Big Creek-Tuolumne River Watershed on the Stanislaus National Forest summarized for 30-year periods. Points represent the average while lines indicate range of data. Data source CalAdapt: See Table 4 footnote. Days above freezing and nights above freezing are based on when the daily maximum/minimum exceeds 32°F.

Extreme Heat

As temperatures increase so will the number of extreme heat events and warm nights (based on exceeding the 98th percentile for what is currently considered hot for the specific area between April and October based on average maximum temperature (extreme heat) and minimum temperature (warm nights). The change in extreme heat days is predicted to be greater for the upper elevation watershed (Clark Fork Watershed) (Figure 14). By the end of the century, in the upper elevation watershed the average number of warm nights increases by 50 days (from 4 to 54 days), while the average number of extreme heat days increases by 47 days (from 4 to 51 days). By the end of the century, in the lower elevation watershed (Big Creek-Tuolumne River Watershed) the average number of warm nights increases by 47 days (from 4 to 51 days), while the average number of extreme heat days increases by 43 days (from 3 to 46 days).

Precipitation

Similar to historic patterns, predicted changes in annual precipitation across the Stanislaus National Forest is variable with a large range in annual minimum and maximum precipitation (Figure 15). In general, precipitation is predicted to increase under both RCP 4.5 and 8.5 scenarios, although there is high variability (Table 5, Figure 15). Annual average maximum precipitation is projected to increase by up to 3.2 inches in the early part of the century (2010-2039) and by 8.4 inches to 19.3 inches by the end of the century (2070-2099) (Table 5).
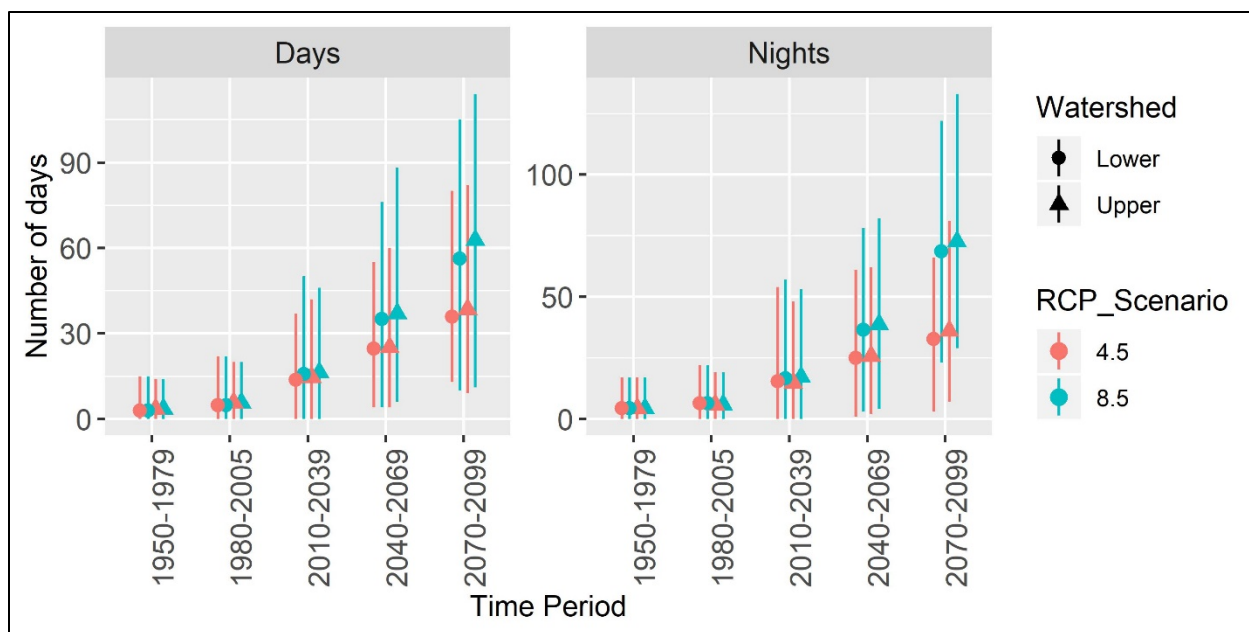
Figure 14. Modeled extreme heat days and warm nights for the Clark Fork Watershed and the Big Creek-Tuolumne River Watershed on the Stanislaus National Forest summarized for 30-year periods. Points represent the average while lines indicate range of data. Data is based on the 98th percentile for what is currently considered extremely hot for the specific area between April through October. The 98th percentile for extreme heat (maximum temperature) is 80.3°F and 97.0°F and for warm nights (minimum temperature) is 47.6°F and 61.7°F for the Clark Fork Watershed and the Big Creek-Tuolumne River Watershed , respectively. Data source CalAdapt: See Table 4 footnote.

The high degree of variation in precipitation is in part driven by the frequency of extreme precipitation events, ranging from zero to 19 events predicted for a single year (Figure 16). Due to the large degree of interannual variability in the occurrence of extreme events, the average number of extreme precipitation events is predicted to increase only slightly (2 in 1950-1979 to 5 in the upper watershed in 2070-2099). This minor increase in mean number of events is likely due to an increase in the maximum number of annual events increasing over time from 11 events in 1950-1979 to 19 events in the lower watershed in 2070-2099. While the number of extreme events only increases slightly, the intensity of extreme precipitation events is predicted to increase more dramatically (Figure 17). By the end of the century total rainfall occurring in extreme precipitation events could increase by 2.3 inches (total average of 12.5 to 14.8 in) in the lower watershed and by 5.9 inches in the upper watershed (total average of 16.4 in to 22.3 in) (Figure 17).

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 more dry years (Pierce et al. 2018). Berg and Hall's (2015) analysis of 34 global climate models project that extremely dry wet seasons 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).

Table 5. Modeled historic and future annual average precipitation on the Stanislaus National Forest summarized for 30-year periods for emission scenarios RCP 4.5 and 8.5. Projected future change compared to modeled historic (1950-1979) temperatures is presented in parentheses.

Annual Average Precipitation (inches)	1950-1979	1980-2005	2010-2039		2040-2069		2070-2099	
	Modeled Historical		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Minimum	20.2	20.9	18.4 (-1.8)	20.5 (+0.3)	21.1 (+0.9)	17.2 (-3.0)	21 (+0.8)	21 (+0.8)
Average	48.2	48.2	52.5 (+4.3)	51.6 (+3.4)	50.4 (+2.2)	50.9 (+2.7)	50.8 (+2.6)	55.8 (+7.6)
Maximum	90.6	91.9	93.8 (+3.2)	90.6 (0)	107.2 (+16.6)	106.6 (+16)	99 (+8.4)	109.9 (+19.3)

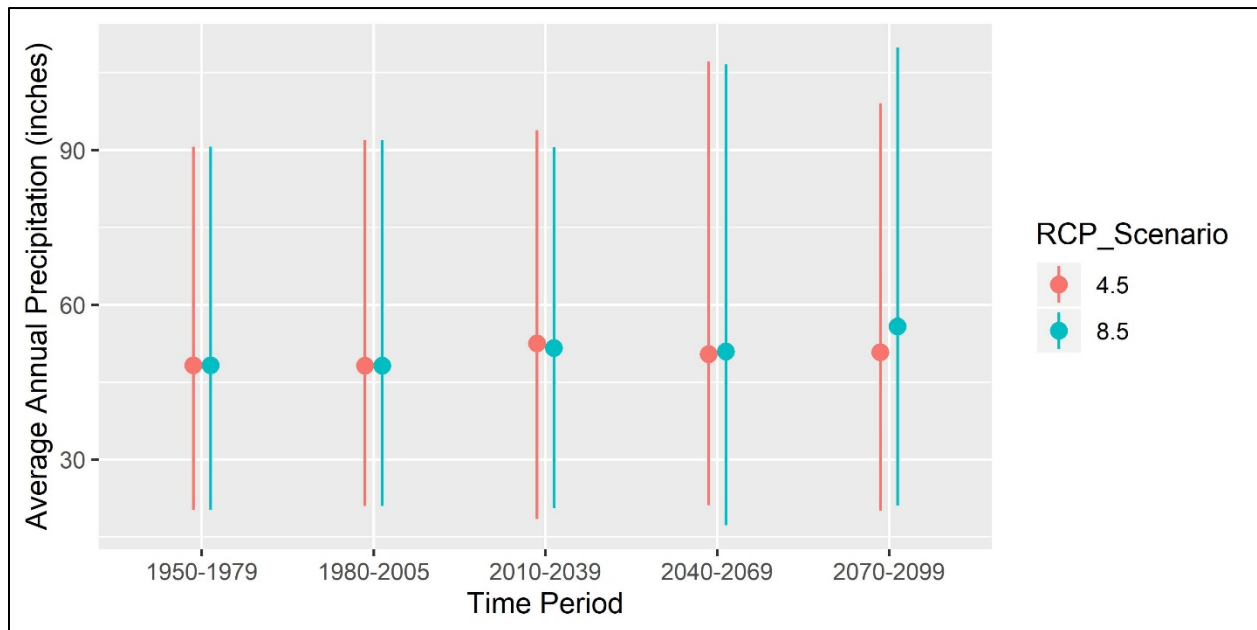Data source CalAdapt: See Table 4 footnote.

Figure 15. Modeled historic and future average annual precipitation on the Stanislaus 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.
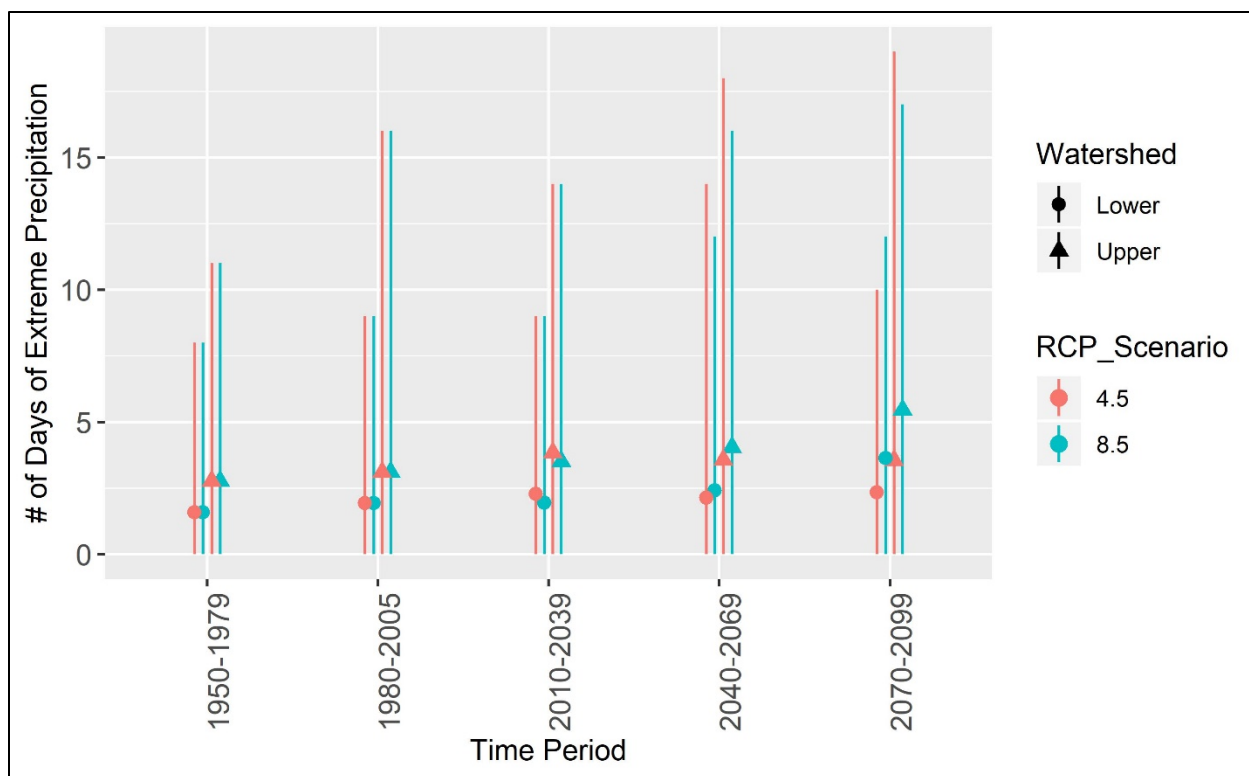
Figure 16. Modeled number of days of extreme precipitation in a water year with 2-day rainfall totals above the extreme threshold for the Clark Fork Watershed (2.97 inches) and the Big Creek-Tuolumne River Watershed (2.85 inches) on the Stanislaus National Forest summarized for 30-year periods. Points represent average, while lines indicate the minimum and maximum. Data source CalAdapt: See Table 4 footnote.

Snowfall

Snow water equivalent is projected to decrease across the Stanislaus National Forest (Figure 18, Table 6) over the coming century. By the end of the century (2070-2099) there will be a projected decrease of 4.1-7.0 inches of SWE (Figure 18, Table 6). This decline in SWE is due to a decreased snow-to-rain ratio (Huang et al. 2018).

Future predicted snowpack declines for the Stanislaus National Forest are similar to predicted changes for California. As climate warms, the Sierra Nevada snowpack will dramatically diminish with only the highest peaks maintaining historical levels of snow by mid-century (Pierce and Cayan 2013). Seasonal snowline is predicted to rise 980 feet in elevation for each 3.6°F increase in temperature. Once temperatures increase by 7.2°F, areas below 6560 feet are projected to be snow free (Roche et al. 2018). Berg and Hall (2017) estimate future snowpack declines of 60-85% due to anthropogenic warming. Rhoades et al. (2018b) project that western US mountain snowfall will decrease by 30%, snow cover will decrease by 44% and SWE will decrease by 69%. In Yosemite National Park, between 38% and 90% loss of April 1 snow water equivalence is projected, along with a 384 ft upslope movement in snowline for every 3.6°F warming that takes place (Roche et al. 2018). Additionally, the date of peak snowmelt is projected to occur from 3 to 24 days earlier in the season (Hayhoe et al. 2004).
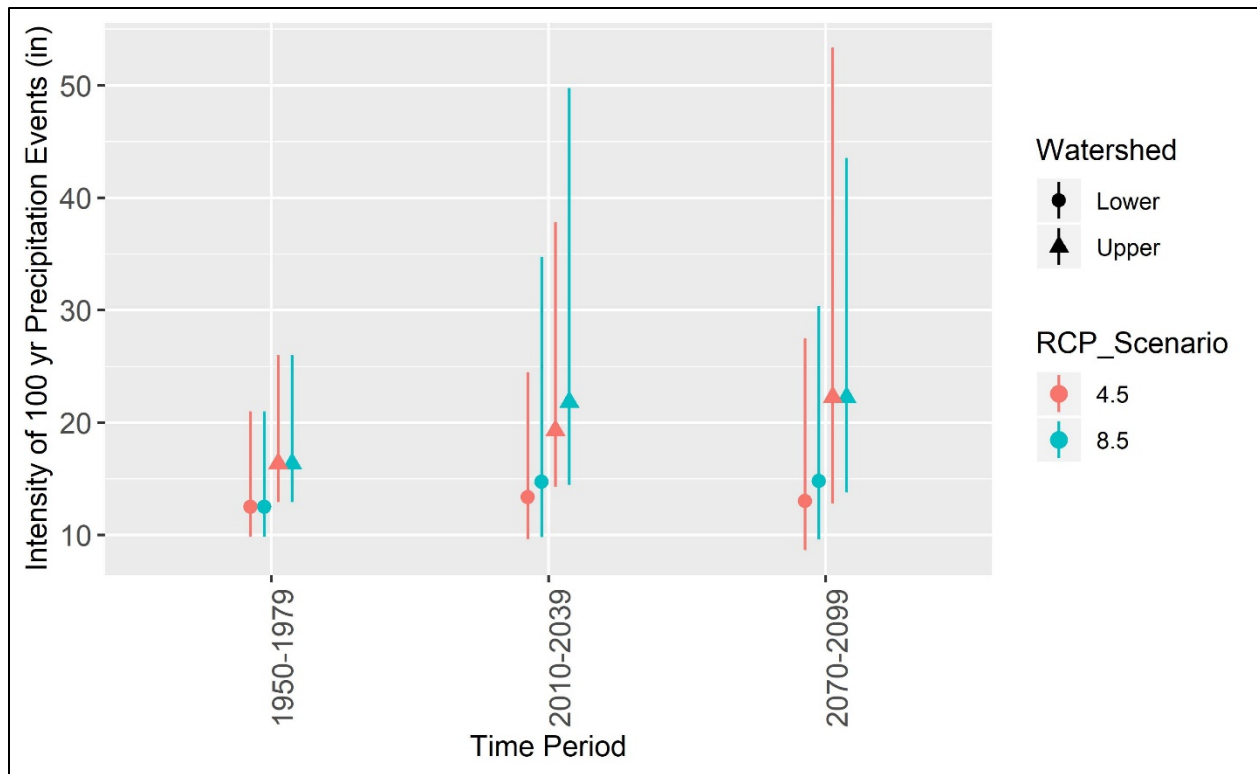
Figure 17. Modeled intensity of extreme precipitation events that on average occur every 100 years for the Upper Watershed (Clark Fork Watershed - 3.34 inches) and the Lower Watershed (Big Creek-Tuolumne River Watershed - 2.85 inches) on the Stanislaus National Forest summarized for 30-year periods. Points represent average, while lines indicate the maximum upper and maximum lower 95% confidence interval. Data source CalAdapt: See Table 4 footnote.

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). While there might be small increases in snowpack at higher elevations, the loss of snowpack at lower elevations (<8200 feet) will overwhelm these increases (Sun et al. 2019). The middle elevations of the Sierra Nevada are expected to experience the most substantial declines in snowpack, with an additional 30-65% decrease projected by the end of the century (Huang et al. 2018).

In the Sierra Nevada, mid-elevation (4,920-8,200 ft) April 1 SWE is projected to decline by 56% under RCP 4.5 and mostly disappear under RCP 8.5, while high elevation (above 8,200 ft) SWE is expected to be reduced by half (Huang et al. 2018). Extreme snow droughts ($\leq$ 10% of historic snow levels) are projected to become nearly continual in the northern Sierra Nevada and four times as likely in the southern Sierra Nevada by the end of the century (Dettinger et al. 2018).

Table 6: Historic and modeled future average annual April 1st Snow Water Equivalent (inches) on the Stanislaus National Forest summarized for 30-year periods for emission scenarios RCP 4.5 and 8.5. Projected future change compared to modeled historic (1950-1979) temperatures is presented in parentheses.

Model	1950-1979	1980-2005	2010-2039	2040-2069	2070-2099
Observed	9.9	10.6 (+0.7)	-	-	-
RCP 4.5	-	-	9.8 (-0.1)	6.4 (-3.5)	5.8 (-4.1)
RCP 8.5	-	-	8.7 (-1.2)	5.3 (-4.6)	2.9 (-7.0)

Modeled temperature data was collected from CalAdapt and is 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.
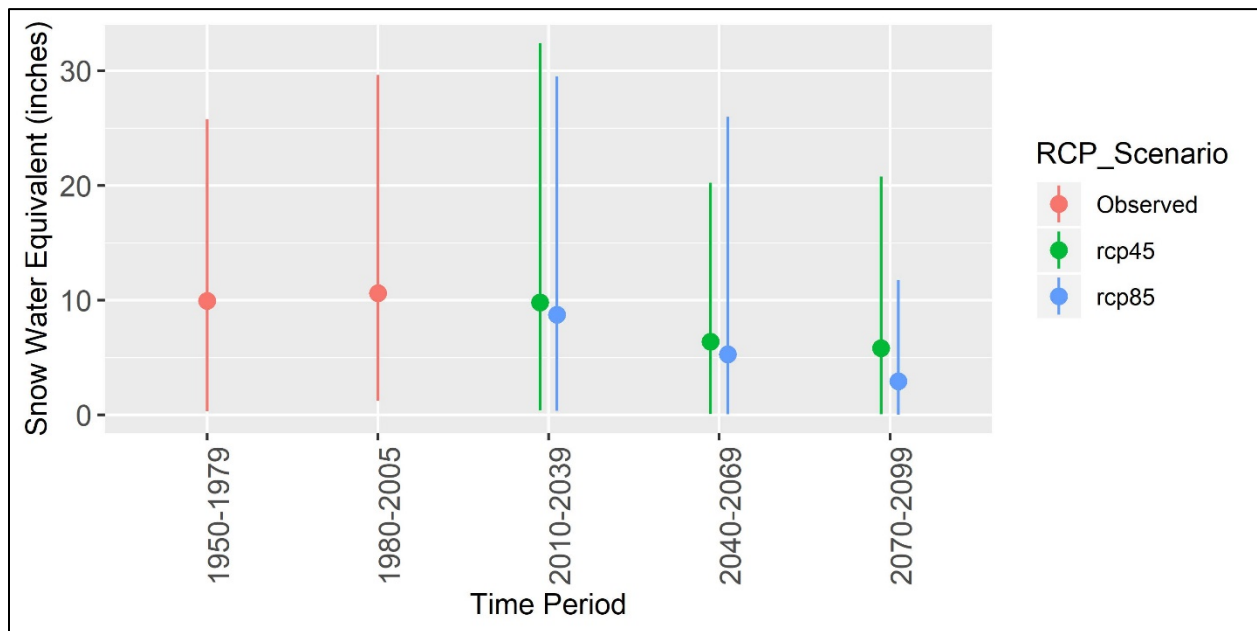
Figure 18: Historic observed and future predicted April 1st Snow Water Equivalent (SWE) on the Stanislaus National Forest summarized for 30-year periods under two emission scenarios (RCP 4.5 and RCP 8.5). Points represent average while lines indicate range of data (minimum and maximum). Data source CalAdapt: See Table 4 footnote.

Drought

Periods of extended drought will make the Stanislaus 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 also 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 from (2051–2070) identified from the HadGEM2-ES RCP 8.5 simulation for two watersheds on the Stanislaus 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	Clark Fork Watershed			Big Creek-Tuolumne River Watershed		
	1961-1990	2023-2042	2051-2070	1961-1990	2023-2042	2051-2070
Ave Maximum Temperature (°F)	53	57.7	61.5	68.1	72.8	76.5
Ave Minimum Temperature (°F)	25.6	29.6	33.3	39.6	43.8	47.3
Ave Precipitation (in)	54.5	46.3	46.3	38.5	31.7	31.7
Snow Water Equivalent (in)	3930.7	1993.3	947.2	120.2	20.1	7.2
Baseflow (in)	17.9	15.3	15.3	10.3	5	4.3
Runoff (in)	15.1	9.3	8.2	5.8	4.7	4.6

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

Future Hydrology Trends

Future climate related hydrological changes anticipated in the Sierra Nevada and Southern Cascade Ranges 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 of the Sierra Nevada (He et al. 2019).

Snowmelt Timing/ Peak Runoff

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 under a high emission climate scenario, that peak snowpack will occur one month earlier by the end of the century, and the peak water volume will be 79.3% lower, with the largest reductions expected in the Shasta, Oroville, and Folsom watersheds at elevations between 0 and 6500 ft (Schwartz et al. 2017, Rhoades et al. 2018a). 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).

There will also be increased variability in runoff volume, both geographically and over time. The northern Sierra Nevada will see large reductions in runoff, while the central Sierra Nevada watersheds will see smaller reductions. Runoff in the southern watersheds will also decrease, though they never produced much runoff in the first place (Rheinheimer et al. 2014). The south-central watersheds are most susceptible to changes in runoff timing and the central watersheds are likely to be impacted by long periods with low flow conditions. When runoff in all of the major Sierra Nevada watersheds was considered, the American and Mokelumne Rivers were most vulnerable to changing flow patterns, while the Kern River was the most resilient, in part due to the high elevations of the watershed (Null et al. 2010).

While overall runoff is generally predicted to decrease, an increase in extreme runoff events is simultaneously predicted. Basins in the northern and central Sierra Nevada are projected to experience substantial increases in extreme runoff, with doubling of the magnitude of high flow events possible for some basins. By end of the century, the contribution of high-magnitude runoff (>90th percentile) to total runoff is projected to increase by 46 to 56%, when averaged across all 12 Sierra Nevada basins (Wrzesien and Pavelsky 2020).

Soil Moisture

Warming temperatures will increase evaporative demands resulting in 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) (Figure 19). 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). Stream temperatures are projected to rise and dissolved oxygen to diminish, creating inhospitable conditions for cold-water fish species (Ficklin et al. 2013b). For every 3.6°F rise in air temperature, a 2.9°F rise in stream temperature is expected, thus significantly reducing Sierra Nevada coldwater habitats (Null et al. 2013). 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). Geographic variability is anticipated, with higher increases in stream temperature in the low-elevation sub-basins of the southern Sierra Nevada compared to more moderate changes in the northern extent of the range (Ficklin et al. 2013a).
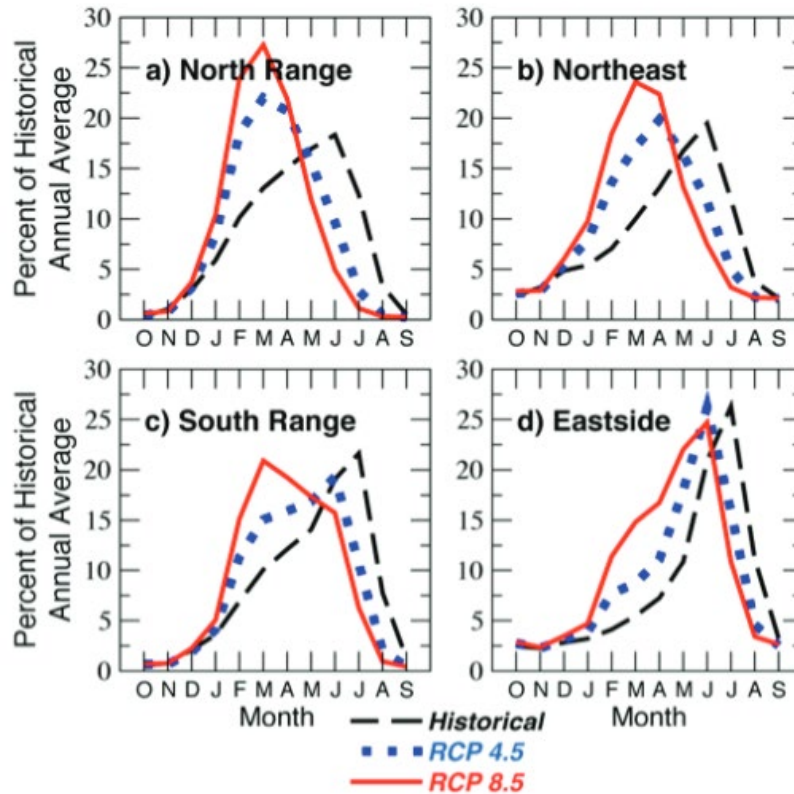
Figure 19. Ensemble averages of 2070-2099 runoff hydrographs for the Sierra Nevada subregions shown in Fig. 1.1a—with each month's runoff shown as a percentage of the historical (1961-1990) annual-total norms--from ten climate models responding to two greenhouse-gas futures, where "runoff" is the water that avoids evaporation and use by plants to flow off or into land surfaces (essentially, surface water flows and groundwater recharge generated by a given area). Notably (d) Eastside responses shown mostly reflect snowmelt and runoff from the eastern slopes of the Sierra Nevada. Adapted from (Dettinger et al. 2018).

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). After modeling 9 headwater basins of the Sierra Nevada and the coastal ranges Luo et al. (2013) found that projected streamflow increased in the winter but then decreased in the summertime. Similarly, when modeling 21st century hydrological changes in five upper headwater basins in the Upper San Joaquin River Watershed, He at al. (2019) found peak projected streamflow will occur 5-16 days earlier than under baseline conditions (1970-1990). Additionally, between -41 and +16% more variability in streamflow volume is projected (He et al. 2019). A high degree of variability is projected for Calaveras 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 with a sharp decline in streamflow in the warmer and drier scenario (Figure 20).

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 in the Sierra Nevada, as precipitation from other precipitation sources dwindles 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). Such events could facilitate unprecedented debris flow and landslide events within the region, such as those documented in the King's River drainage and other recent case studies (e.g., (DeGraff et al. 2011, Huggel et al. 2012).
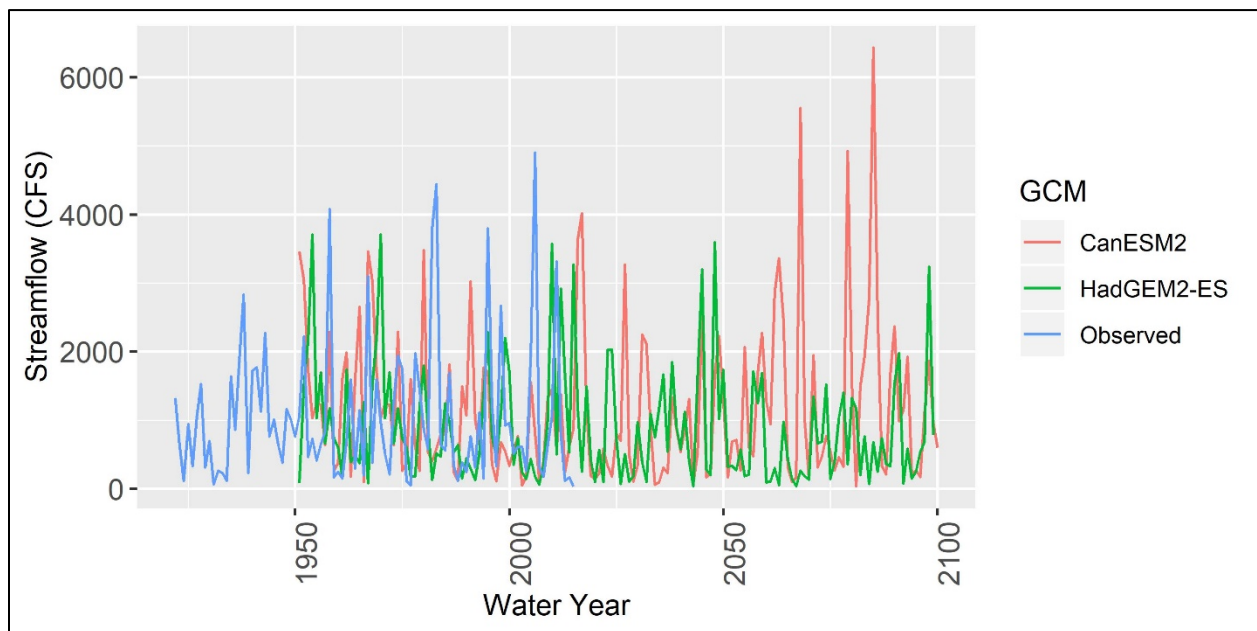
Figure 20. This chart shows total annual unimpaired flows in a water year (October – September) for June, July, and August. Data are shown for Calaveras River at Jeremy Lind under the RCP 8.5 scenario in which emissions continue to rise strongly through 2050 and plateau around 2100. Values represent observed streamflow (1922-2015) and global climate models (GCM) of CanESM2 (an average simulation) and HadGEM2-ES (a warm/drier simulation).

More flooding in higher-elevation, snowmelt-fed California rivers is 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). In another study, all 16 climate projections for a high greenhouse gas scenario projected larger floods returning every 2-50 years throughout the Sierra Nevada, irrespective of how precipitation changes, with flood flows increasing from 30 to 100% (Harpold et al. 2015). However, the increase in flooding events may not persist over time. For instance, flooding events that would have historically occurred once every hundred years are projected to increase in frequency in the Tahoe Basin up to 2.5 fold by the middle third of the century and then decline with an increasingly warmer and drier climate (Coats et al. 2013).

Hydrology Management Recommendations

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). Hydrologic function can be restored through the reintroduction of beaver populations to meadows and streams. Previous assertions that beaver (*Castor canadensis*) did not occur in the Sierra Nevada can be attributed to heavy trapping practices prior to early wildlife studies being performed in the 1900s (Lanman et al. 2012). Beaver populations likely thrived in the Sierra Nevada and evidence of historical beaver dams has been observed as high as 5,500 feet in the Sierra Nevada (James and Lanman 2012) and there are historical reports of beaver in relatively high elevations throughout both slopes of the Sierra Nevada (Lanman et al. 2012). Given the dramatic role that beavers play as ecosystem engineers by developing more resilient riverine systems (Pollock et al. 1995, Wright et al. 2002) reintroducing beaver would greatly contribute to the amount of water held in the mountains for longer, helping to mitigate problems associated with earlier runoff and flooding events while maintaining more water for forests, meadows and wildlife.

Forest density reduction and managed wildfire also provide opportunities to manage the hydrologic regime. While impacts of the drought on mountain runoff in the southern Sierra Nevada were exacerbated by a 1.8°F increase relative to the previous decade, they were mitigated by wildfire and drought-associated tree mortality. Once tree and understory mortality had occurred, total evapotranspiration lessened, thus leaving more water available for runoff (Bales et al. 2018). A wildfire-restored basin in Yosemite National Park maintained higher snow-water equivalent than control areas in the 2012-2016 drought, and overall, annual streamflow, subsurface water storage and peak snowpack all increased relative to a fire-suppressed control (Boisramé et al. 2019).

Future Fire Trends

Current trends of increasing fire activity and severity are predicted to continue into the future. Several comprehensive reviews of the wildland fire literature have found overwhelming evidence that area burned and fire number 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% for 2046–2055 relative to 1996–2005, and that mid-elevation sites on the west side of the Sierra Nevada would experience the greatest increases.

For California's fourth Climate Change assessment, (Westerling 2018) simulated fire activity across California from 1953 to 2099. 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. In the Sierra Nevada annual average acres burned were projected to double or to quadruple by the end of century (Figure 21).

For the Stanislaus National Forest, data compiled by (2018) also project that total acres burned will increase by the end of this century (Figure 22). For the lower elevation watershed, Big Creek-Tuolumne, historical (1954-1979) averages of between 1926 and 1983 acres burned annually which are projected to increase to between 2619 and 3805 acres burning annually by the end of the century. In the higher elevation Clark Fork watershed, historical annual averages of between 314 and 317 acres burned are projected to increase to between 691 and 1765 acres burned annually by the end of the century.
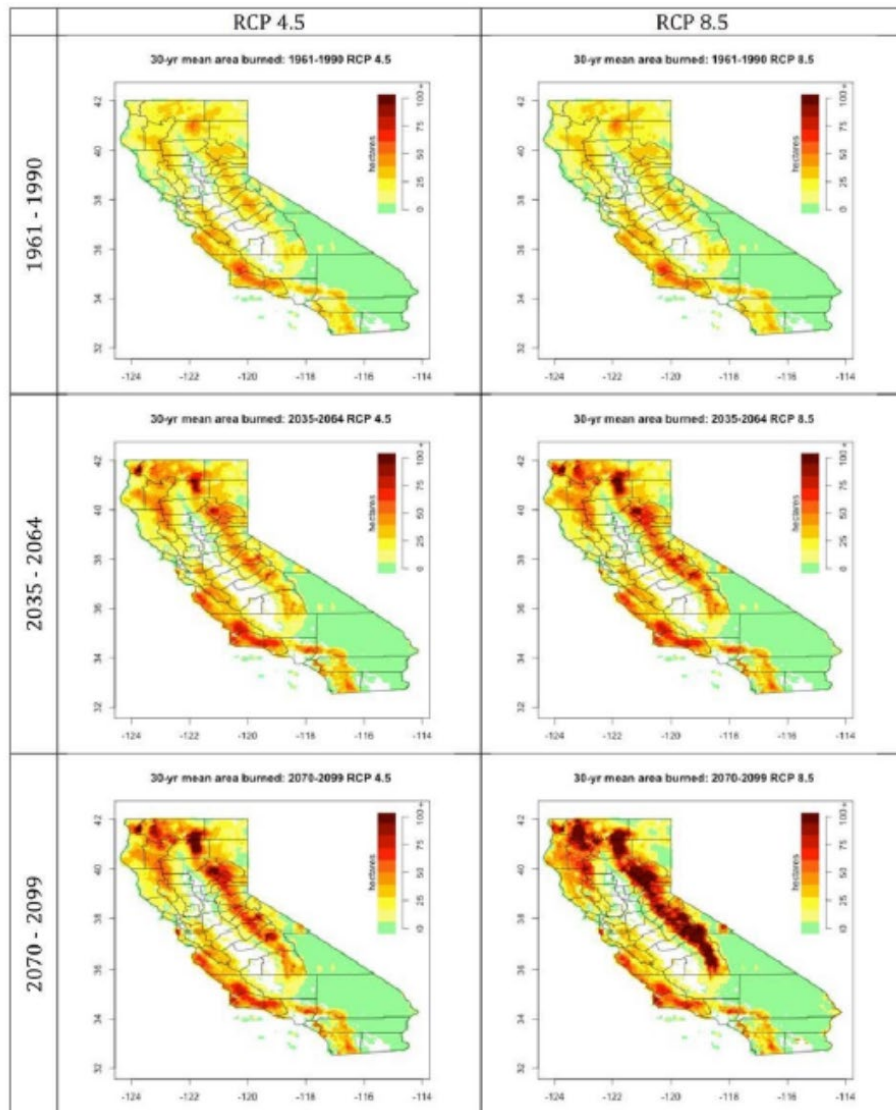

Figure 21. Average annual area burned composites: RCP 4.5 (left), RCP 8.5 (right) from Westerling (2018).
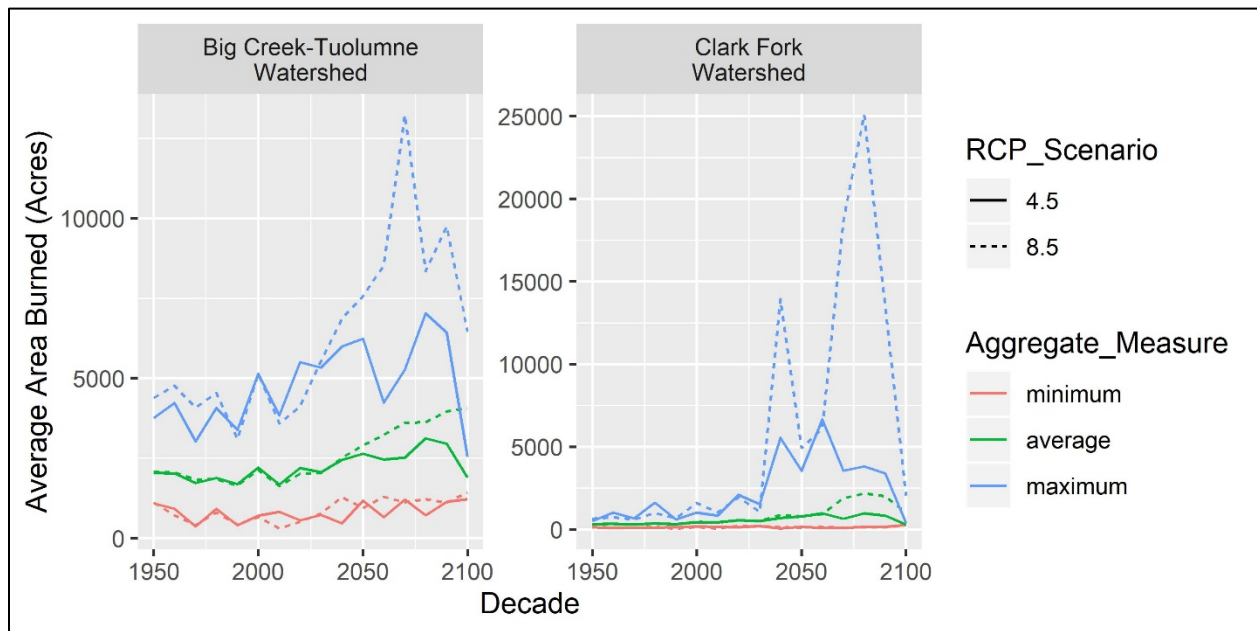
Figure 22. Wildfire simulations for two watersheds on the Stanislaus National Forest smoothed by decade. Data source CalAdapt using wildfire scenario projections produced by (Westerling 2018).

A number of models project that fire severity will also continue to increase in the western US throughout the 21st century (Abatzoglou and Williams 2016, Abatzoglou et al. 2017, McKenzie and Littell 2017). As the number of acres burned in the Sierra Nevada increases, so will the number of acres burned at high severity (Miller and Safford 2012, Keyser and Westerling 2019). (Lutz et al. 2009b) projected that annual area burned at high severity in Yosemite National Park will increase by about 20% by 2020-2049. 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.

Effects of projected temperature, fuel aridity, and fire season length on future fire activity

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 Sierra Nevada. 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 connectivity 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.

Effects of projected snowpack and lightning on fire activity

Fires may also become more frequent and severe as a result of reduced snowpack and increased lightning ignitions in the future. Using one snowpack forecast, Lutz et al. (2009b) projected that the number of lightning-ignited fires will increase 19%, and the annual area burned at high severity will increase 22%, by 2049 in Yosemite National Park. 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.

Potential effects of tree mortality on future fire activity

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 and Safford 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 mass fires over longer time frames (Stephens et al. 2018, Westerling 2018, Coop et al. 2020). The recent widespread tree mortality in the Sierra Nevada is without historical analog and is beyond the scope of current fire and fuel models to accurately evaluate (Stephens et al. 2018, Westerling 2018).

Fire Management Recommendations

Although future emissions scenarios will largely determine future wildfire activity, human activity, particularly population growth and land-use change, will also play a key role (Keeley and Syphard 2015). Mann et al. (2016) found that anthropogenic influences, including ignitions, fire suppression, land use patterns, and development, explained almost 50% of historic fire activity. One way that human activities could reduce future fire risk is by reducing fuel loads. Fuel treatments, such as the proactive use of fire through prescribed burning and wildland fire use, as well as restoration thinning, have the potential to mitigate predicted increases in burned area in the Sierra Nevada (Littell et al. 2009, Hurteau et al. 2019, Stephens et al. 2020). Westerling (2018) modeled a management scenario where almost 30% of the vegetated area was treated to reduce fuels and found that area burned decreased by 16-31% in the Sierra Nevada by the end of the century compared with 1961-1990. Krofcheck et al. (2017) modeled the effects of prescribed burning and thinning on the Sierra National Forest and found that in combination, these treatments could reduce mean fire severity by 25%, even during extreme fire weather. They also found that predicted carbon emissions were lowest in the thin and maintenance burning scenario, even when accounting for the carbon costs associated with prescribed burning. In addition, prescribed burning and restoration fuel treatments provide additional ecological benefits including enhanced biodiversity, increased water availability, greater long-term and

more sustainable carbon storage, improved forest resilience and adaptation to climate change, and reduced air pollution (Coop et al. 2020, Stephens et al. 2020).

Future Vegetation Trends

Future climate change will have direct effects on vegetation (Breshears et al. 2005) and intensify stressors such as fire and drought contributing to indirect changes 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. (2018) used a Community Land Model to determine vulnerability to mortality from drought and fire by 2049. They found vulnerability to future fire will be the highest in the Sierra Nevada (Buotte et al. 2018).

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). Most changes in forest distribution are predicted to be on the west slope of the Sierra Nevada (Liang et al. 2017). In the foothills, the models project declines in shrubland and oak woodlands and an increase in grassland due to higher fire frequencies (Lenihan et al. 2003, Lenihan et al. 2008). Projections in mid elevations include modest declines in conifer-dominated forests and their subsequent replacement by hardwood-dominated forest (Lenihan et al. 2003, Lenihan et al. 2008, Liang et al. 2017). In higher elevation forests, red fir is projected to increase in distribution, likely capturing subalpine zones that might become more climatically suitable (Lenihan et al. 2003, Lenihan et al. 2008, Liang et al. 2017).

Structure and Composition of Forests

Climate models suggest forest community composition in California in the late century may not change substantially, but community composition will be greatly simplified as the least tolerant species can no longer establish (Liang et al. 2017). Climate will have direct effects on vegetation 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 forest 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). Under potential future scenarios of higher summer temperatures and reduced precipitation, most mature trees will have lower survival and reduced growth, leading to shifts in species composition and more open forest structure (Scheller et al. 2018, Moran et al. 2019). Conifer-dominated forest in the Sierra Nevada could shrink as recruitment is reduced, primarily at the low to mid-elevations (Liang et al. 2017, Moran et al. 2019). Similar shifts in subalpine conifer forests are projected, however long lived subalpine trees can arguably absorb more environmental change (Dolanc et al. 2013). Recruitment at higher elevations may experience initial boosts as climatic conditions are more favorable but late century will likely see similar reductions in recruitment (Dolanc et al. 2013, Liang et al. 2017).

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 would be even more pronounced following extreme drought periods (Stevens et al. 2017, Young et al. 2019).

Some climate models project decreasing precipitation and 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 as the climate becomes warmer and drier (Dodson and Root 2015, Parks et al. 2018), leading to an increase in dominance of graminoids and shrubs in post fire landscapes as woody vegetation retracts in the face of increased fire frequency (Crockett and Westerling 2018).

Climate vulnerability is defined as exposure, sensitivity and adaptive capacity to a changing climate and are good tools to assess susceptibility of major forest types in the Sierra Nevada 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%) Forested areas in the Sierra Nevada region are predicted to be 45% (hotter and wetter scenario) to 62% (hotter and drier scenario) highly climatically stressed under current emission levels (RCP8.5) by 2070-2099 (Thorne et al. 2017). These value are reduced under similar climate models under RCP4.5 emissions (Thorne et al. 2017). Climate exposure or the level of change in climate conditions expected on the Stanislaus National Forest range from seven percent of the landscape at high stress between 2011-2039, 17% by 2040-2069 and 68% by 2070-2099 under a drier and wetter global climate model at emission level RCP8.5 (Figure 23). These numbers are considerably higher under the hotter and drier global climate model at emission level RCP8.5. Thorne et al. (2018) assessed climate exposure and vulnerability (defined as exposure, sensitivity, and adaptive capacity) of ten major forest types in the Southwest at 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).
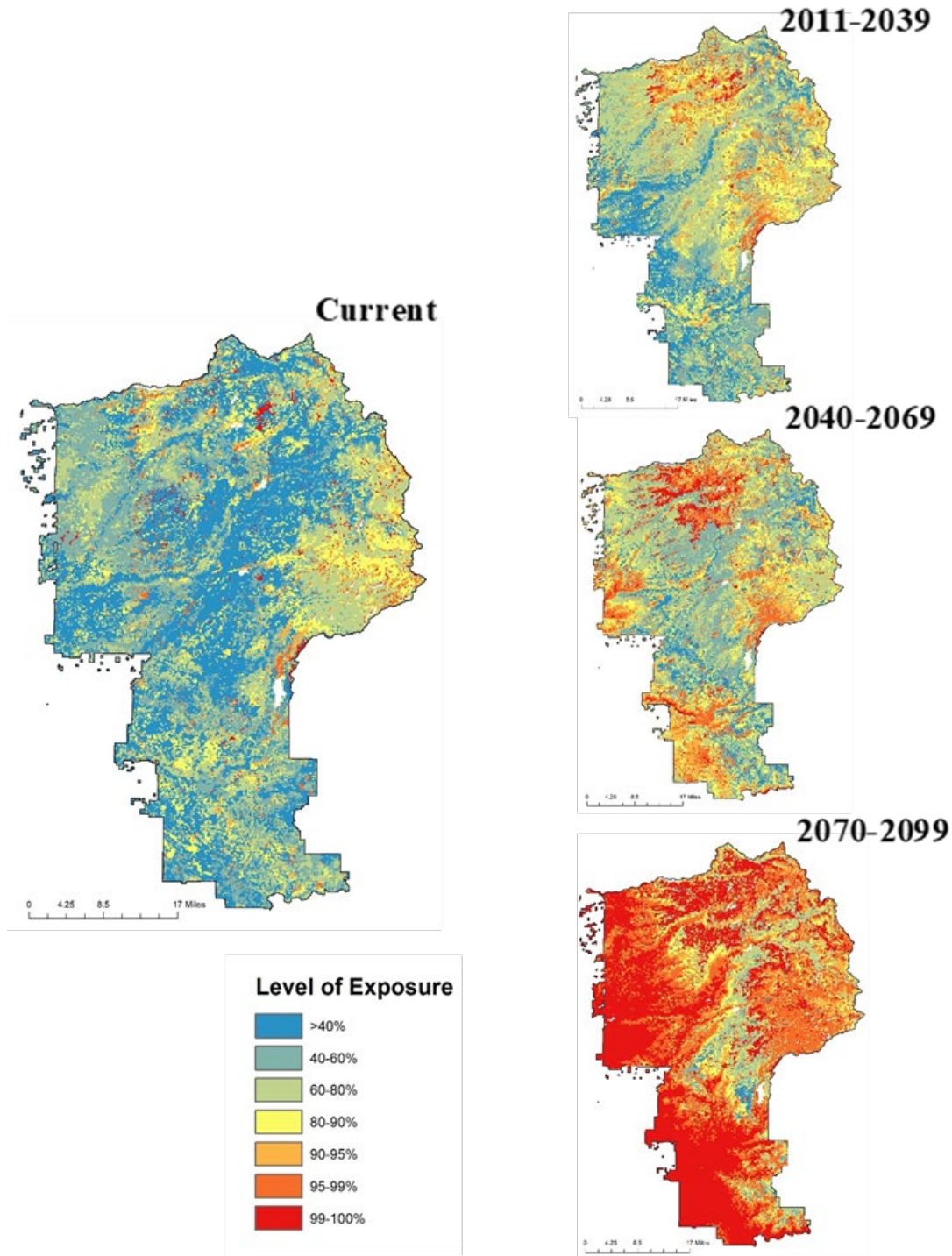
Figure 23. Mapped climate exposure under the "Warm and Wet" CNRM CM5 climate projection under Higher Emissions RCP8.5. This image shows the climate exposure of Stanislaus National Forest vegetation types at current time and three future periods: 2011–2039, 2040–2069, and 2070–2099. Areas considered to be highly climatically exposed are in the 95–99% and 99–100%. Areas with values <80% are considered to be in climatically suitable conditions for the vegetation that it currently occupies.

Future Drought Trends

Moisture stress and the frequency and severity of bark beetle outbreaks are projected to increase dramatically with increasing temperatures in the Sierra Nevada, resulting in widespread tree mortality comparable to or greater than the 2012-2016 drought (Bentz et al. 2010). 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. These projected changes will potentially increase tree mortality in the Sierra Nevada by 15-20% per degree of temperature increase (Goulden and Bales 2019).

Vegetation Management Recommendations

Reducing competition via management actions such as thinning may increase climatic resilience for all species and have positive results for competitors (Johnson et al. 2017, Vernon et al. 2018, Restaino et al. 2019). In addition, management could help reduce stress from subsequent fires through mechanisms such as growth release (Van Mantgem et al. 2018). However, interactions between climate and competition can be complex, and effects may vary by species, region, tree age, and tree size.

There are a number of predictive tools that managers can use to help make climate-wise decisions. After the 2012-2016 drought managers needed a way to plan for reforestation. The reforestation prioritization tool (https://climate-wise.shinyapps.io/reforest_toolkit/) was designed to help locate where to reforest based on the level of tree mortality and other user-defined variables. The post-drought stand condition tool was designed to allow users to explore newly changed conditions on their National Forest area of interest.

Understanding pre-mortality indicators is important to prioritize at-risk forests. Sustained water loss and gross mortality are strongly related and year to year water loss within the drought were indicative of subsequent mortality (Brodrick and Asner 2017). In order to better predict drought stress and to understand susceptibility of forest types, methods are being developed to help managers understand where areas of high vulnerability to mortality might exist (Brodrick and Asner 2017, Byer and Jin 2017).

Managers should use quantitative information that details a tree's response to climate, disturbance and stand conditions to develop forest management regimes. This can be accomplished by collecting pertinent variables that help predict post management mortality (Van Mantgem et al. 2018).

Future Meadow Exposure to Changes in Climate

We used the Sierra Nevada Meadow Climate Vulnerability assessment dataset to identify future meadow exposure (Albano et al. 2019, Gross et al. 2019). Exposure is based on the relative change in April 1st snowpack between 1981-2010 and 2040-2069 using the climate model MIROC-RCP8.5 (Gross et al. 2019). We chose this climate model, which projects increased temperatures combined with decreased rainfall because future drought will be more detrimental to meadow health compared to an increase in precipitation (Arnold et al. 2014). High exposure areas are where there will be the greatest change in future snowpack based on the MIROC-RCP8.5 climate model. Based on this analysis, most of the meadows on the Stanislaus National

Forest are projected to have high (38%) to medium (37%) exposure with only 26% of the meadows projected to experience low exposure (Figure 24). Gross et al. (2019) provides information on how to combine meadow sensitivity and exposure, as well as adaptive capacity to evaluate future vulnerability to changes in April 1st snowpack.
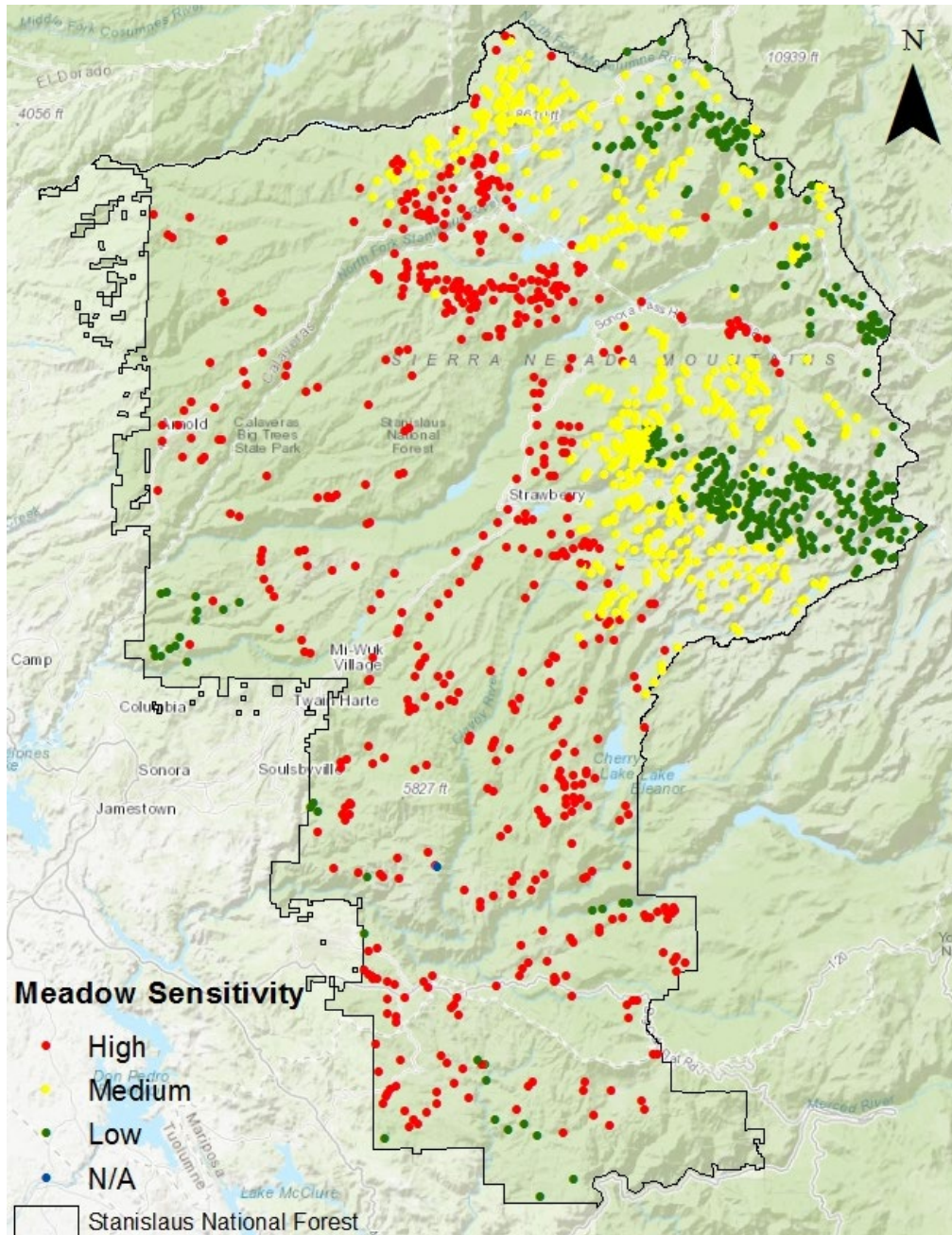

Figure 24. Future exposure of meadows on the Stanislaus National Forest based on the relative change in April 1st snowpack between 1981-2010 and 2040-2069 using the climate model MIROC-RCP8.5.

Future Wildlife Trends

Direct Impacts

Physiological effects and range shifts

Significant changes to California's wildlife populations are projected over the next century. The California Avian Data Center (2011) projected that approximately 60% of 21 coniferous forest bird species in the Sierra Nevada will exhibit substantial range reductions within the next 40 to 90 years. 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 species such as the great gray owl, greater sage grouse, and gray-crowned rosy finch (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. Stewart et al. (2017) project significant declines in climatically suitable habitat for pika, characterized by areas with refugial mean summer temperature (MST) less than 57.6 °F. The area of refugial conditions for pika in the Tahoe study region is projected to decline by 97% by 2050.

As the southern Sierra Nevada becomes warmer and receives less precipitation as snow, martens will experience conditions that fall outside their historical climatic thresholds (Zielinski et al. 2017) and thus are likely to experience range contraction. Even under projected wetter future climate scenarios, stable or increasing precipitation is unlikely to outweigh the negative impacts of increasing temperature on marten distribution as precipitation shifts from snow to rain. Lawler et al. (2012) found that macroclimate conditions closely correlated with marten and fisher presence in California were likely to change greatly over the next century, suggesting that the two species will be highly sensitive to climate change and will probably experience the largest climate impacts in the southern Sierra Nevada. Additionally, increases in summer temperatures, as well as increases in temperature variability, are likely to reduce fisher distribution in more extreme or exposed locations (Zielinski et al. 2017). However, fishers on the Kern Plateau, a high elevation site that receives relatively low precipitation, may be able to capitalize on future snow reduction to expand their range upslope (Zielinski et al. 2017).

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, even in the upper elevations of the Sierra Nevada, where only a modest proportion of novel avian communities are projected to occur (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. 2011). 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, Western red bat) will likely experience declines in prey detection abilities as temperatures rise, while those with lower frequencies (e.g. pallid bat, Townsend's big-eared bat, fringed myotis) may experience increased prey detection abilities, altering the balance of these predator/prey relationships (Luo et al. 2014).

Increasing temperatures and diminishing snowpack are projected to allow for the expansion of some species' ranges into those of competing species. These climate trends will allow fishers to expand their range to higher elevations, increasing areas of overlap with marten habitat, particularly in the southern Sierra Nevada (Zielinski et al. 2017). Zielinski et al. (2017) explain that since fishers and marten have similar diets, increased likelihood of interaction means increased competition that could negatively affect one or both species.

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 in the Sierra Nevada 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.

Projected increases in temperature and decreases in snowpack for the Sierra Nevada are likely to continue the increasing trend in the size of stand-replacing fires and proportion of landscape impacted by those fires (Stephens et al. 2013). 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 1994, 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). In the long term, these threats may be somewhat mitigated by mixed-conifer forests moving upslope, developing habitat for owls where none now exists (Peery et al. 2012). However, development of suitable forest structure at higher elevations will likely take many decades and may not keep pace with habitat loss at lower elevations (Stephens et al. 2016). In fact, Stephens et al. (2016) suggest that within the next 75 years, the cumulative amount of spotted owl nesting habitat burned at high or moderate/high severity (greater than 50 percent basal area mortality) will exceed the total existing habitat today. 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 in the Sierra Nevada (Blakey et al. 2020). Bat species, on the other hand, are expected to maintain resilience to increases in fire severity and size with a changing climate, as species richness was found to increase with severity for several bat species in the Sierra Nevada (Steel et al. 2019).

Wildlife Management Recommendations

Habitat refugia and connectivity, though not long-term solutions, will be important for maintaining species resilience to climate change. Genetic evidence suggests that fishers have survived climate-driven range contraction in the past, and that the southern Sierra Nevada may have acted as a climate refugium (Tucker et al. 2014, Zielinski et al. 2017). For the spotted owl high elevation sites with higher canopy cover are likely to serve as the best refugial sites (Jones et al. 2016b). Therefore, increasing presence and resilience of large tree, closed canopy forests at higher elevations is an important aspect of developing future refugia for spotted owls, fishers, and martens (North et al. 2017, Zielinski et al. 2017). North et al. (2017) recommend managing these potential refugia for cooler, moister forest types. Further, maintaining connectivity between lower elevation mid-century refugia and higher elevation end-century refugia will become important to aid in species migration as refugial patterns shift upslope.

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 in the near future, 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). 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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