A summary of current trends and probable future trends in climate and climate-driven processes in the Stanislaus National Forest and the neighboring Sierra Nevada

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I. Local and regional trends in climate over the past century

The data presented in this section are derived primarily from three weather stations with long-term meteorological records from the general area of the Stanislaus National Forest ("STF"). The longest quasi-continuous weather record is provided by the Yosemite National Park station ("YOSE-NP") (1907-2012; WRCC 2012) located in Yosemite Valley, which is near the southern portion of the STF, approximately 13 miles east of the boundary between STF and Yosemite National Park. The Yosemite Valley station lies at about 4000 feet at approximately 37º 45.0' N, 119º 35.0' W. The elevation of the station and surrounding vegetation are representative of the area of the STF within which management activities are proposed. The YOSE-NP weather record is missing precipitation data from 1923 and 1980 (WRCC 2012). A combined 100-year dataset (1912-2009) is available from two stations near the south-central portion of the STF: the Lake Eleanor station (4800 feet asl; 37º 58.44' N, 119º 52.66' W), which is found at the boundary the STF and Yosemite National Park and provides a 44-yr record from 1912-1955; and the nearby Cherry Lake station, (4760 feet asl; 37º 58.48' N, 119º 54.98' W), which provides a 56-yr record from 1956-2012 (WRCC 2012). Analyses for Lake Eleanor and Cherry Lake stations were combined because of the close proximity (2 miles distance) and similarity in elevation and topography of these two stations. In this document, reference is also made to weather records from an 83-year dataset (1929-2012) at the Calaveras Big Trees State Park station (4780 feet asl; 38º 17.0' N, 120º 19.0' W), which is found within the northwestern portion of the STF (WRCC 2012). We also present spatial data from the PRISM climate dataset, which extrapolates weather station records to the landscape for all years beginning in the late 19th century (Daly et al. 1994, PRISM 2010).

We evaluated weather 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. Temperature values for individual calendar-years (i.e., January–December) were calculated 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. Precipitation totals were calculated for water-years (i.e., July–June) because water-year precipitation totals are i) more clearly linked to the availability of water for natural ecosystems and human populations during the annual summer droughts, and ii) of greater importance for understanding flood risks to low-lying areas. Individual years were withheld from trend analyses if any non-summer month (i.e., September–May) 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. Annual snowfall totals were calculated by water-year. The presence, direction, and magnitude of climatic trends were assessed through simple linear regressions using ordinary least squares estimation procedures. Trend analyses were performed using only data from stations and time periods for which climate data were more than 70% complete.

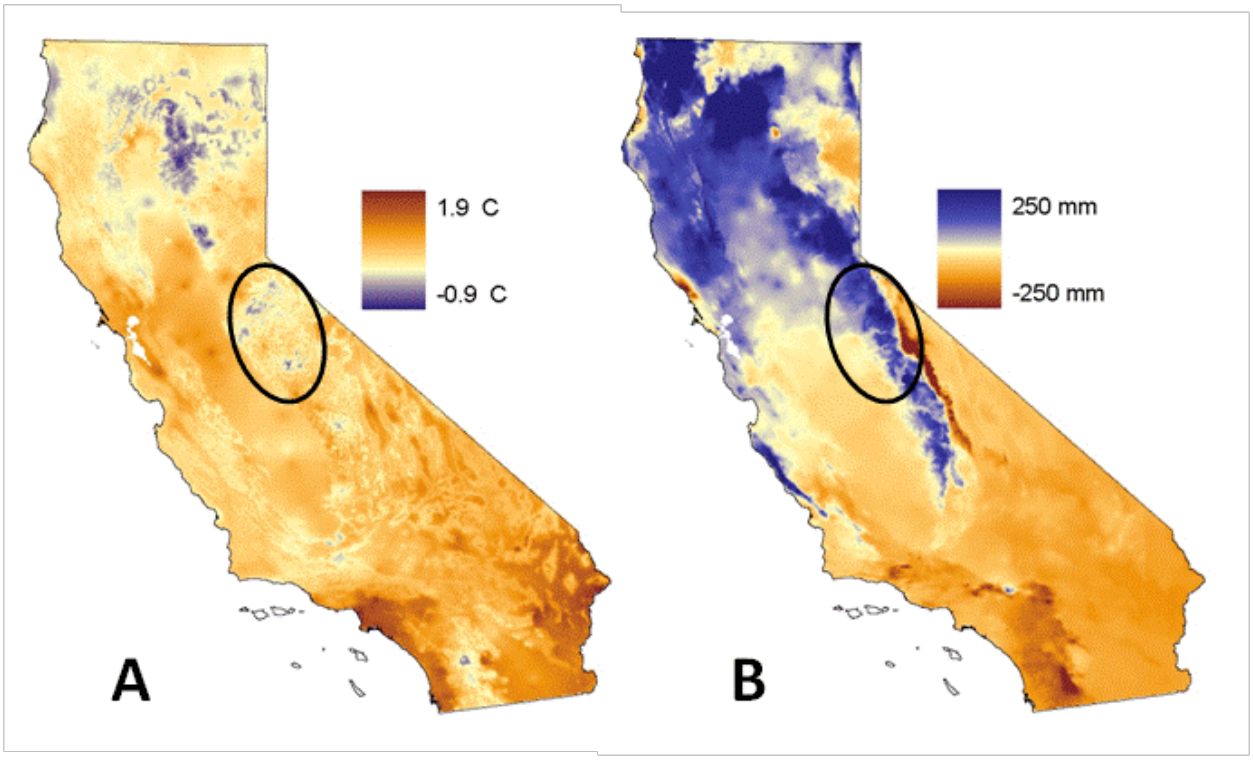


Figure 1. Spatial differences in mean annual temperature (A), and mean annual precipitation (B) between the 1930's and 2000's, as derived by the PRISM climate model. The Stanislaus NF area is found within the circle. Temperatures have risen across most of the STF area, while precipitation increases are limited to higher elevations. Graphic courtesy of S. Dobrowksi, Univ. of Montana.

Temperature

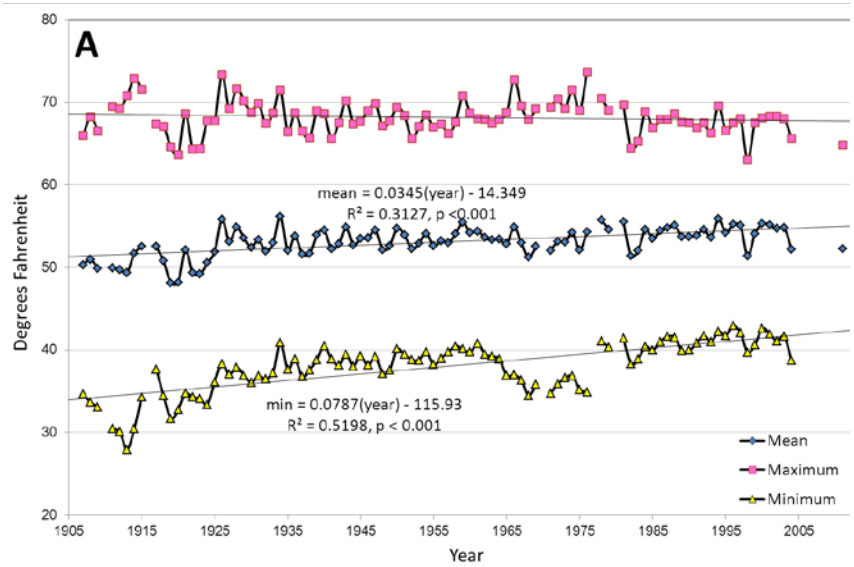
The PRISM data suggest that most of the Stanislaus NF area has experienced increases in temperature of 1ºC (1.8 ºF) or more over the last ¾ century, although some isolated areas have seen no change or even a decrease in temperature (Fig. 1). The weather station data agree. For example, over the last century, mean annual temperature at the Yosemite Valley station has risen

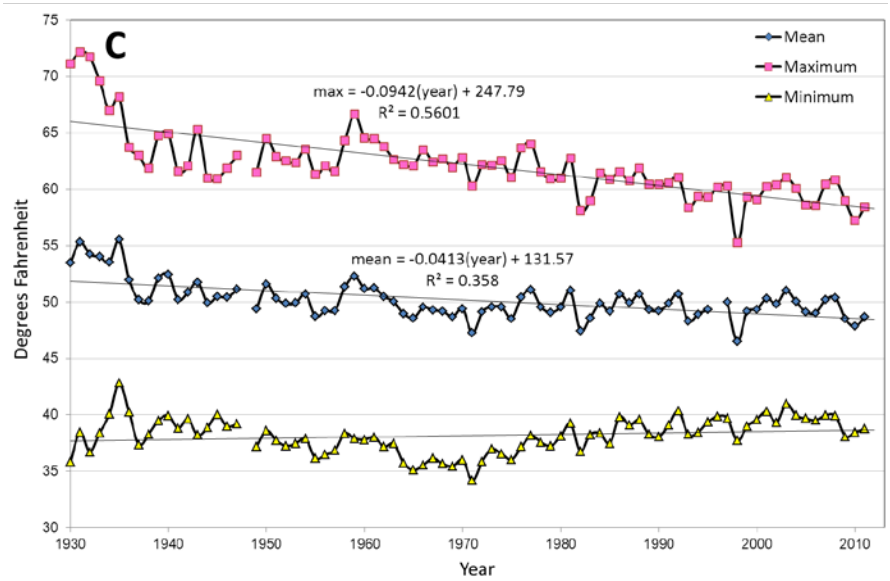
by about 3.5º Fahrenheit (Table 1; Fig. 2a; values from regression equation). This trend is driven by a highly significant increase in mean minimum (i.e., nighttime) temperatures, which have risen by 7.6º F since 1915. At the beginning of the record, the annual average of the monthly mean minima was just above the freezing point (34º F), but it is now approximately ten degrees above the freezing point (Fig. 2a). The 100-year record from Lake Eleanor and Cherry Lake stations shows a similar trend (Table 1; Fig. 2b). Mean annual temperatures at Lake Eleanor and Cherry Lake stations have risen by about 2.5º F since 1912, and nighttime mean minima have risen by about 4.0º F; the mean maxima have risen by 1.3º F. Increasing annual temperatures, especially in the past 30 years, are consistent with other climate analyses both in the southern Sierra Nevada (Edwards and Redmond 2011, Gonzalez 2012) and at higher elevations in the region (Diaz and Eischeid 2007, Das and Stephenson 2012). In contrast, at the Calaveras Big Trees station the mean annual temperature over a 82-year record declined by about 3.4°F since 1930 and the mean maxima have declined by about 7.7° F (Table 1; Fig. 2c). The mean minimum temperatures have shown a non-significant increasing trend. The occurrence of nighttime freezing temperatures has been decreasing over the last century. For example, at the beginning of the Yosemite Valley data record approximately 6 months in a year could be expected to have average nighttime temperatures that fell below freezing. Today the average is closer to three months, and the trend is strongly downward (Table 1; Fig. 3). A similar trend has been observed at Lake Eleanor and Cherry Lake, where average nighttime temperatures below freezing declined from 4.3 months a year to 2.8 months a year (Table 1; Fig. 3).

Table 1. Direction, magnitude, and statistical significance of climatic shifts at Yosemite NP, Lake Eleanor/Cherry Lake, and Calaveras Big Trees Stations. Numerical values indicate the difference between the expected values for the earliest and most recent years of the given time frame, as calculated using regression equations. Directions and magnitudes of shifts 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, while those for temperature are organized by calendar-year. Data gaps of more than 3 consecutive years are noted.**

	Yosemite National Park 1907-2012	Lake Elaeanor/ Cherry Lake 1912-2012	Calaveras Big Trees 1930-2012
Elevation	4000 feet asl	4800 feet asl	4780 feet asl
Temperature			
Mean (°F)	+3.5***	+2.5***	-3.4***
Max. (°F)	ns	+1.3*	-7.7***
Min. (°F)	+7.6***	+4.0***	ns
Freezing (mo/yr)	-2.9***	-1.5***	ns
Precipitation			
Total (in.)	ns[1]	+11.7*	ns
Coefficient of variation	ns[1]	+0.37***	ns
Snowfall (in.)	-51.0*[2]	ns[3]	-52.7[4]

1. Missing 1916-1926, 2004-2012; 2. 1943-2003 only, missing data from: 1978-1981, 1985-1988; 3. 1924-2012; 4. 1949-2011





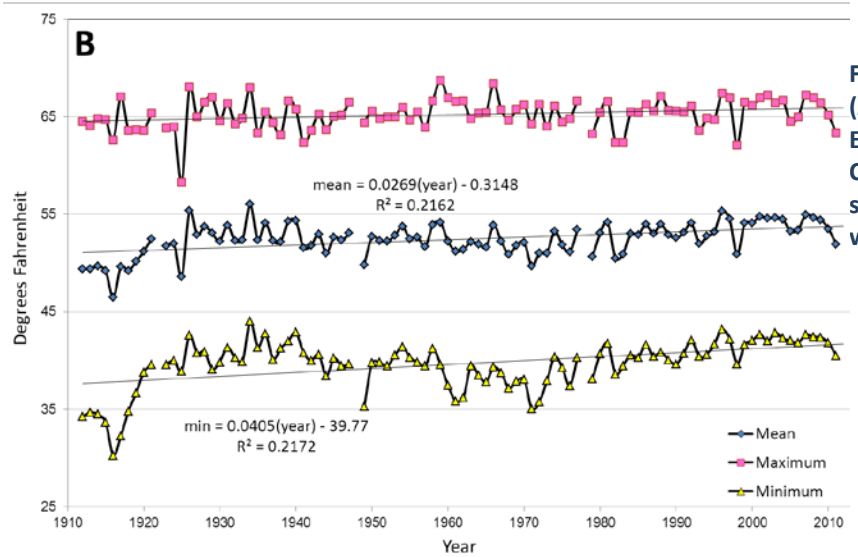


Figure 2. Annual mean, mean maximum, and mean minimum temperatures at (A) Yosemite National Park in Yosemite Valley, California, 1907-2012; (B) Lake Eleanor/Cherry Lake, CA, 1912-2012; and (C) Calaveras Big Trees State Park, CA, 1930-2012. Linear regression equations, coefficients of determination, and statistical significance shown for significant regressions. No transformations were employed

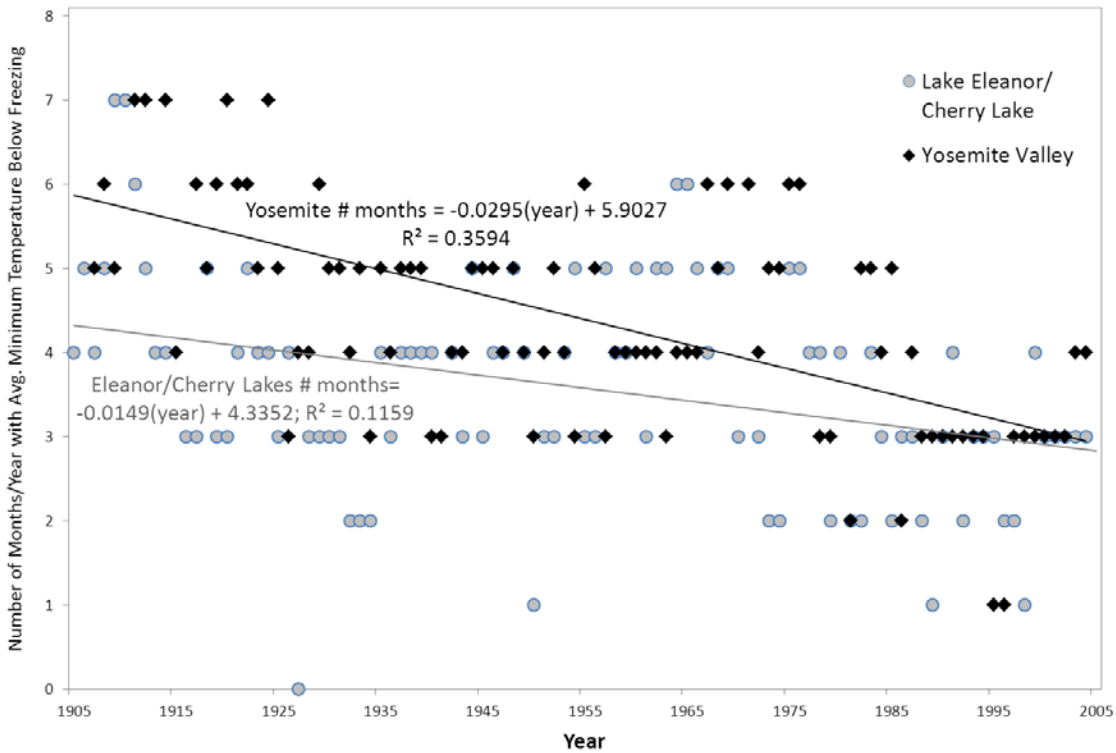


Figure 3. Number of months with the monthly mean minimum temperature remaining below freezing at Yosemite Valley, 1907-2012 and Lake Eleanor and Cherry Lake, 1912-2012. Trend lines fit with simple linear regression. Data from WRCC 2012.

Precipitation

While trends in total precipitation vary greatly from site-to-site, some general changes in precipitation patterns have been observed across the western United States since the mid-1900s. These shifts include: more rainfall and less snowfall (Knowles et al. 2006); decreased snow depth (particularly at lower, transitional elevation sites; Grundstein & Mote 2010; Barnett et al. 2008; Mote et al. 2005); and decreased snow-water-equivalent (SWE) as proportion of precipitation (by 2-8% per decade with the exception of high elevation areas like the Southern Sierra Nevada; Barnett et al. 2008, Mote et al. 2005). Local and subregional precipitation trends in the Sierra Nevada range from negative to positive (WRCC 2012), and trends at even nearby stations can vary widely. The 105-year dataset at Yosemite Valley and the 82-year dataset from Calaveras Big Trees show no discernable change in mean annual precipitation (Table 1). The Lake Eleanor-Cherry Lake shows an increase in total precipitation of approximately 11.7 inches over the last century (Fig. 4), but there is very high and increasing interannual variability, such that the value predicted by the regression line in Fig.4 is rarely representative of the actual annual mean. In addition, the great increase predicted by the regression line is driven to a notable extent by a small number of extreme precipitation years, such as 1982, 1983, and 1995. The PRISM dataset suggests that most higher elevation locations in the Stanislaus NF area have experienced increases in precipitation, while most lower elevation locations have seen precipitation drop (Fig. 1).

As is the case with precipitation itself, interannual variability in precipitation varies from station to station. At Lake Eleanor and Cherry Lake, the 5-yr coefficients of variation of annual precipitation increased significantly over time (Fig. 5a), which demonstrates that year-to-year variability in precipitation has increased over the course of the last century. Contrastingly, Yosemite Valley and Calaveras Big Trees (Fig. 5b,c ; WRCC 2012), showed no significant trends in interannual precipitation variability, although they showed generally high variability overall. Similar to Eleanor/Cherry Lakes, interannual variability in rainfall at the Sequoia and Sierra National Forests has increased over the past century (Meyer and Safford 2010).

Declining snowpack and snowwater equivalent trends were observed in the central Sierra Nevada (Fig. 6) including the Stanislaus NF area. Like precipitation in general, however, there are great differences in snowfall trends between different sites. For example, between 1943 and 2003 total annual snowfall at Yosemite Valley declined from around 80 inches to 30 inches (Table 1, Fig. 7; WRCC 2012) and the snowfall at Calaveras Big Trees declined from a predicted 150 inches to 98 inches annually between 1949 and 2011 (Table 1; Fig. 7). On the other hand, total annual snowfall at Lake Eleanor and Cherry Lake (1924-2012) did not change significantly over time (Table 1; WRCC 2012).

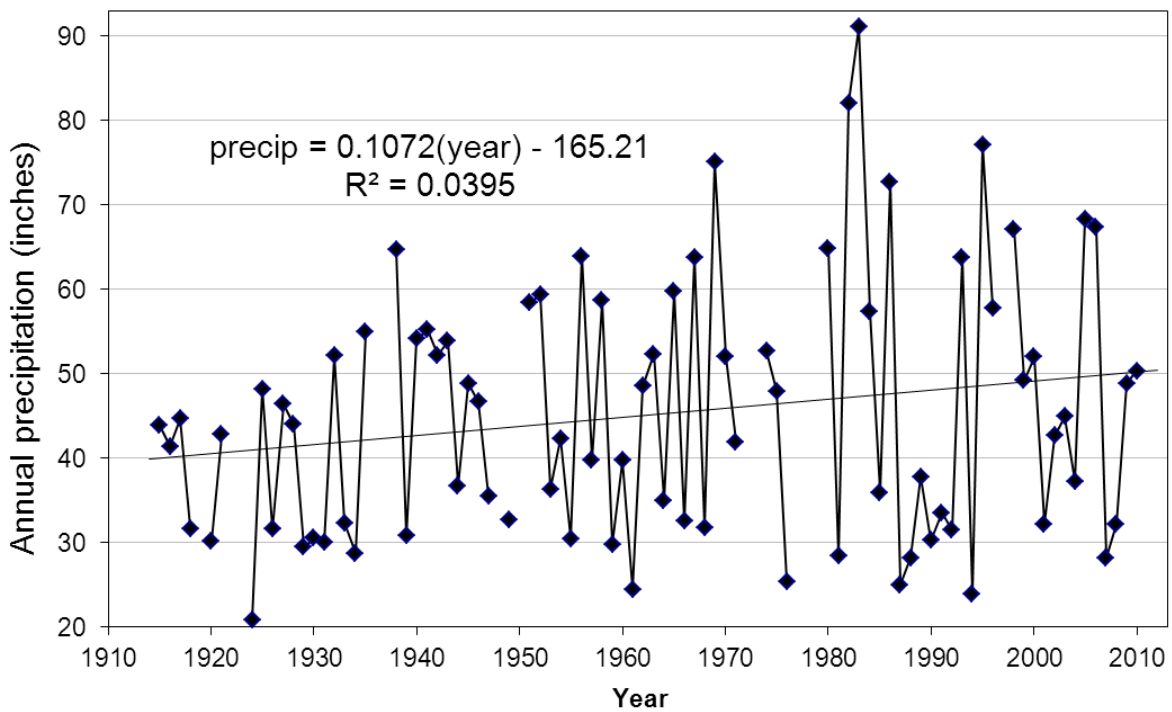


Figure 4. Mean annual precipitation at Lake Eleanor and Cherry Lake, 1912-2012. Trendline fit with simple linear regression, no transformations employed. Data from WRCC 2012.

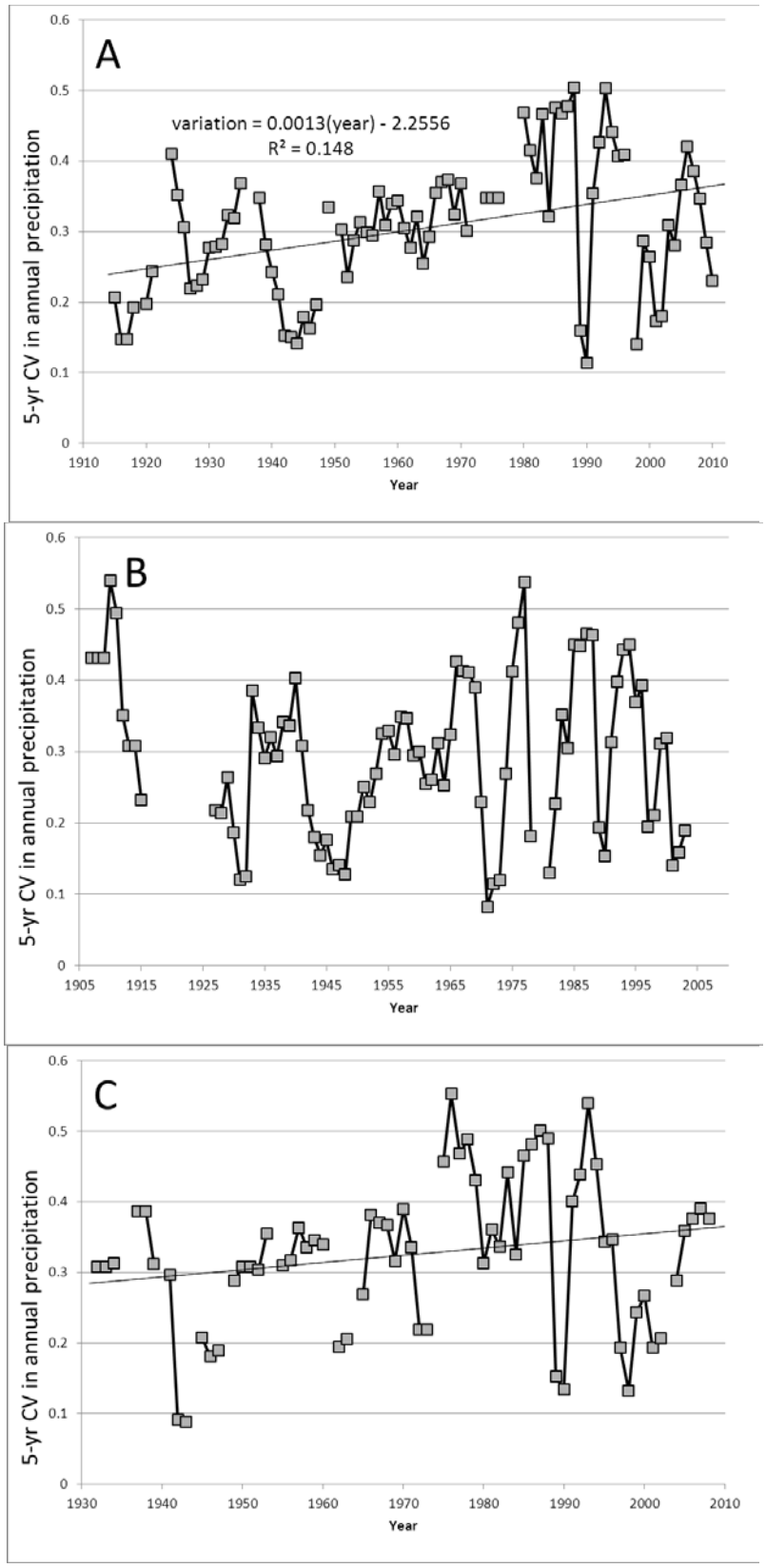


Figure 5. Five-year coefficients of variation in annual precipitation at:

(A) Lake Eleanor and Cherry Lake, California, 1912-2009;

(B) Yosemite National Park in Yosemite Valley, CA, 1907-2012;

(C) Calaveras Big Trees State Park, CA, 1930-2012.

Linear regression equations, coefficients of determination, and statistical significance shown for significant regressions.

Data from WRCC 2012.

II. Regional trends over the last century linked to climate change

Hydrology

Across the western United States, widespread changes in surface hydrology have been observed since the mid-1900s. These shifts include: earlier snow melt and spring runoff (by 0.3 to 1.7 days per decade; Barnett et al.2008; Hamlet et al. 2007; Stewart *et al*. 2005; Maurer 2007); decline in total runoff occurring in the spring (Moser et al. 2009); rising river temperatures (Kaushal et al. 2010), and increased variability in streamflow (Pagano & Garen 2005). While individual watershed response to climate change is highly variable (Null et al. 2010), the broad scale trends observed across the Western U.S. have been mirrored on a smaller scale across California and the Sierra Nevada. Over the last half-century, peak runoff/streamflow (measured as the center of mass annual flow) has shifted earlier in the year for many Sierra Nevada watersheds (Young et al. 2009; McCabe and Clark, 2005; Regonda et al., 2005; Stewart et al., 2005). Stewart et al. (2005) showed that the onset of spring thaw in most major streams on the western slopes of the southern Sierra Nevada occurred 5-20 days earlier in 2002 than in 1948, and peak streamflow occurred 0-15 days earlier. Moser et al. (2009) reported that over the past 100 years, the fraction of annual runoff that occurs during April–July has decreased by 23% in the Sacramento basin and by 19% in the San Joaquin basin in California. 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 studied streams (Stewart et al. 2005). Baldwin et al. (2003) found that in the Sierra Nevada and northeastern California, the timing of spring snowmelt driven streamflow is now about 10 to 15 days earlier than in the mid-1900s (Baldwin *et al.* 2003). In addition to temporal shifts, California has also exhibited one of the greatest increases in variability in streamflow in the Western U.S. since the 1980s (Pagano & Garen 2005). This increased variability, coupled with high year-to-year persistence (i.e. the probability that a wet year is followed by another wet year, or a dry by a dry year) has resulted in extended and extreme dry and wet spells that are particularly challenging to manage (Pagano & Garen 2005).

Beneath these general trends, there is much variation in the range of hydrologic response to climate change in the Sierra Nevada, due principally to variation in the locations and elevations of studied watersheds. For example, while the northern Sierra Nevada shows a decrease in snow-water-equivalent as proportion of precipitation (SWE/P) since 1950, the southern Sierra Nevada actually shows a positive trend (Barnett et al. 2008) or positive but insignificant trend (Christy and Hnilo 2010). This discrepancy is largely owing to the generally higher elevations in the southern Sierra Nevada, as cold, high elevation areas, and those with very large increases in precipitation, showed positive trends in SWE from 1950 to 1997 (Mote et al. 2005). Null et al. (2010) assessed the vulnerability to climate warming of 15 west-slope watersheds in the Sierra Nevada and found differing vulnerabilities for different segments of the mountain range. They found that mid- and high-elevation watersheds in southern-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).

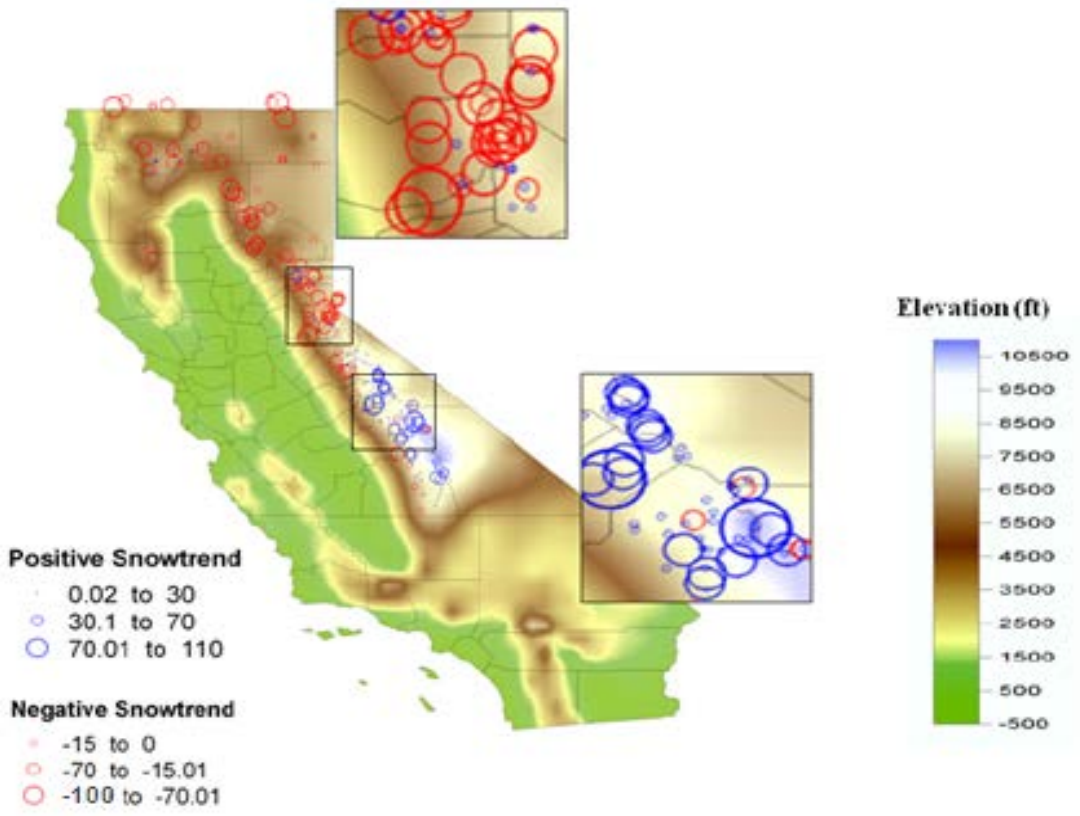


Figure 6. Trends in the amount of water contained in the snowpack ("snow water equivalent") on April 1, for the period 1950-1997. Red circles indicate percent decrease in snow water, blue circles indicate increase in snow water. From Moser et al. (2009).

Forest fires

Data on forest fire frequency, size, total area burned, and severity all show strong increases in the Sierra Nevada over the last two to three decades. Westerling et al. (2006) showed that increasing frequencies of large fires (>1000 acres) across the western United States since the 1980's were strongly linked to increasing temperatures and earlier spring snowmelt. The Sierra Nevada was one of two geographic areas of especially increased fire activity, which Westerling et al. (2006) ascribed to an interaction between climate and increased fuels due to fire suppression. Westerling et al. (2006) also identified the Sierra Nevada has being one of the geographic regions most likely to see further increases in fire activity due to future increases in temperature. Miller et al. (2009) showed that mean and maximum fire size, and total burned area in the Sierra Nevada have increased strongly between the early 1980's and 2007. Climatic variables explain very little of the pattern in fire size and area in the early 20th century, but 35-50% of the pattern can be explained by spring climate variables (spring precipitation and minimum temperature) in the last 25 years. The mean size of escaped fires in the Sierra Nevada was about 750 acres until the late 1970's, but the most recent ten-year average has climbed to about 1100 acres. The model that best explained the increase in area burned in the Sierra

between 1977 and 2003 included effects of summer drought, and precipitation in both growing season and winter in the year prior to fire (Littell et al. 2009).

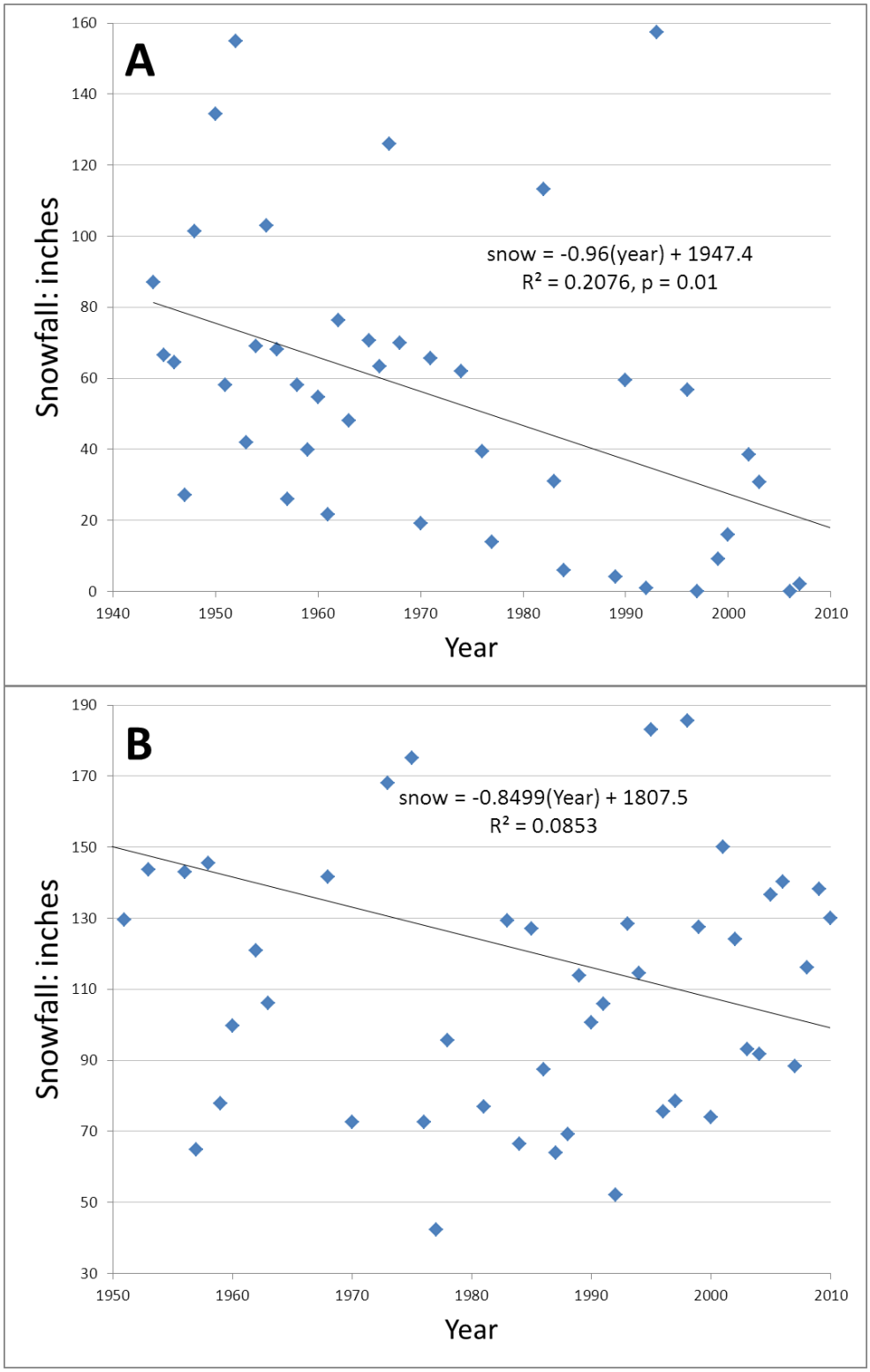


Figure 7. Trends in annual snowfall at: (A) Yosemite National Park in Yosemite Valley, CA, 1907-2012; and (B) Calaveras Big Trees State Park, CA, 1930-2012. Linear regression equations, coefficients of determination, and statistical significance shown for significant regressions. Data from WRCC 2012.

High temperatures, increased fuel production due to winter precipitation, and more severe summer droughts have led to increases in area burned in the past 30 years (Littell et al. 2009). Miller et al. (2009) and Miller and Safford (2012) also showed that forest fire severity (a measure of the effect of fire on vegetation) rose strongly during the period 1984-2007 and 1984-2010, respectively, with the pattern centered in middle elevation conifer forests of the Sierra Nevada. Fires at the beginning of the record burned at an average of about 17% high (stand-replacing) severity, while the average for the last ten-year period was 30%. Miller et al. (2009) found that both climate change and increasing forest fuels were necessary to explain the patterns they analyzed. For mixed conifer forests, Miller and Safford (2012) also documented increases in the total annual area of high severity fire, the percentage of high severity fire in large (>1000 acre) fires, and the total number of large fires.

Forest structure

Fire suppression has been practiced as a federal policy since 1935. Pre-Euroamerican fire frequencies in high elevation forests such as red fir (>50 years in most places) and subalpine forest (>100 years) were long enough that fire suppression has had little or no impact on ecological patterns or processes (Miller et al. 2009). Higher elevation forests are also much more remote, less likely to have economic uses, and are often protected in Wilderness Areas and National Parks, so impacts by logging or recreation use are minimal. Subalpine tree growth has been shown to be strongly influenced by higher precipitation and warm summers (Graumlich 1991). Long-term changes in stand structure in higher elevation forests are thus more likely to represent responses to changes in exogenous factors like climate.

In the early 1930's, the Forest Service mapped vegetation on National Forest lands in the Sierra Nevada, and sampled thousands of vegetation plots (Wieslander 1935). Bouldin (1999) compared the Wieslander plots with the modern FIA inventory and described changes in forest structure for the Sierra Nevada from Yosemite National Park to the Plumas National Forest, i.e. primarily north of the SNF. In red fir forest, Bouldin (1999) found that densities of young trees had increased by about 40% between 1935 and 1992, but densities of large trees had decreased by 50% during the same period. In old-growth stands, overall densities and basal areas were higher, and the number of plots in the red fir zone dominated by shade-tolerant species increased at the expense of species like Jeffrey pine and western white pine. In old-growth subalpine forests, Bouldin (1999) found that young mountain hemlock, a shade-tolerant species, was increasing in density and basal area while larger western white pine was decreasing. In whitebark pine stands, overall density was increasing due to increased recruitment of young trees, but species composition had not changed. Lodgepole pine appears to be responding favorably to increased warming and/or increased precipitation throughout the subalpine forest.

Bouldin (1999) also studied mortality patterns in the 1935 and 1992 datasets. He found that mortality rates had increased in red fir, with the greatest increases in the smaller size-classes. At the same time, in subalpine forests, lodgepole pine, western white pine, and mountain

hemlock all showed decreases in mortality. The subalpine zone was the only forest type Bouldin (1999) studied where mortality had not greatly increased since the 1935 inventory. This suggests that climate change (warming, plus steady or higher precipitation) is actually making conditions better for some tree species in this stressful environment. Dolanc et al. (2012) recently completed a study that resampled Wieslander plots in the subalpine zone between Yosemite National Park and the Lake Tahoe Basin. Corroborating Bouldin (1999), they found that growing conditions in the subalpine zone were probably better today than in the 1930's, as the density of small trees of almost all species had increased greatly in the 75 year period. Dolanc et al.'s (2012) direct plot-to-plot comparison also found that mortality of large trees had decreased density of the subalpine forest canopy, but the overall trend was for denser forests with no apparent change in relative tree species abundances. According to Bunn et al. (2005), high-elevation conifers in the Sierra Nevada and White Mountains showed higher growth rates in the second half of the 20th century than at any other time in the last millennium, and this was correlated with increasing temperatures. Similarly, when Millar et al. (2004) reconstructed changes in Sierra Nevada high elevation treeline ecotones between 1880 and 2002, they found that throughout the 20th century, conifer branch growth accelerated in treeline sites and invasions of snow fields by conifers increased. These changes were correlated with increased minimum monthly temperatures, although they presented more complex relationships with precipitation (Millar et al. 2004). Evidence from treeline ecotone studies suggests that warmer conditions encourage upslope advancement, but that this movement may be limited by moisture availability (Malanson et al. 2007).

Van Mantgem et al. (2009) recently documented widespread increases in tree mortality in old-growth forests across the west, including in the Sierra Nevada. Their plots had not experienced increases in density or basal area during the 15-40 year period between first and last census. The highest mortality rates were documented in the Sierra Nevada, and in middle elevation forests (3300-6700 feet). Higher elevation forests (>6700 feet) showed the lowest mortality rates, corroborating the Bouldin (1999) findings. Van Mantgem et al. (2009) ascribed the mortality patterns they analyzed to regional climate warming and associated drought stress. Lutz et al (2009) found that between the mid-1930s and mid-1990s, both the density and diversity of large-diameter trees in Yosemite National Park declined. Lutz et al (2009) observed a 24% decrease in large diameter tree density across the 21 tree species they measured. They attribute this decline mainly to water stress, and note that declining water availability is likely to disproportionately affect species already occurring close to their water balance limit, such as western white pine and mountain hemlock (Lutz et al. 2010). Damschen et al. (2010) re-surveyed vegetative species cover and richness across sites in the Siskiyou mountains of northern California and southern Oregon 57 years after their original surveys between 1949 and 1951. Although their work was not in the Sierra Nevada, their results suggest that species living in already stressful conditions may have less capacity to tolerate climate change impacts.

Comparisons of the 1930's Wieslander vegetation inventories and map with modern vegetation maps and inventories show large changes in the distribution of many Sierra Nevada vegetation types over the last 70-80 years (Fig. 8, 7b; Bouldin 1999, Moser et al. 2009, Thorne and Safford, unpub. data). The principal trends are (1) loss of yellow pine dominated forest, (2) increase in the area of forest dominated by shade-tolerant conifers (especially fir species), (3) loss of blue

oak woodland, (4) increase in hardwood dominated forests, (5) loss of subalpine and alpine vegetation, and (6) expansion of subalpine trees into previous permanent snowfields. Trends (4) through (6) appear to have a strong connection to climate warming, while trends (1) through (3) are mostly the product of human management choices, including logging, fire suppression, and urban expansion.

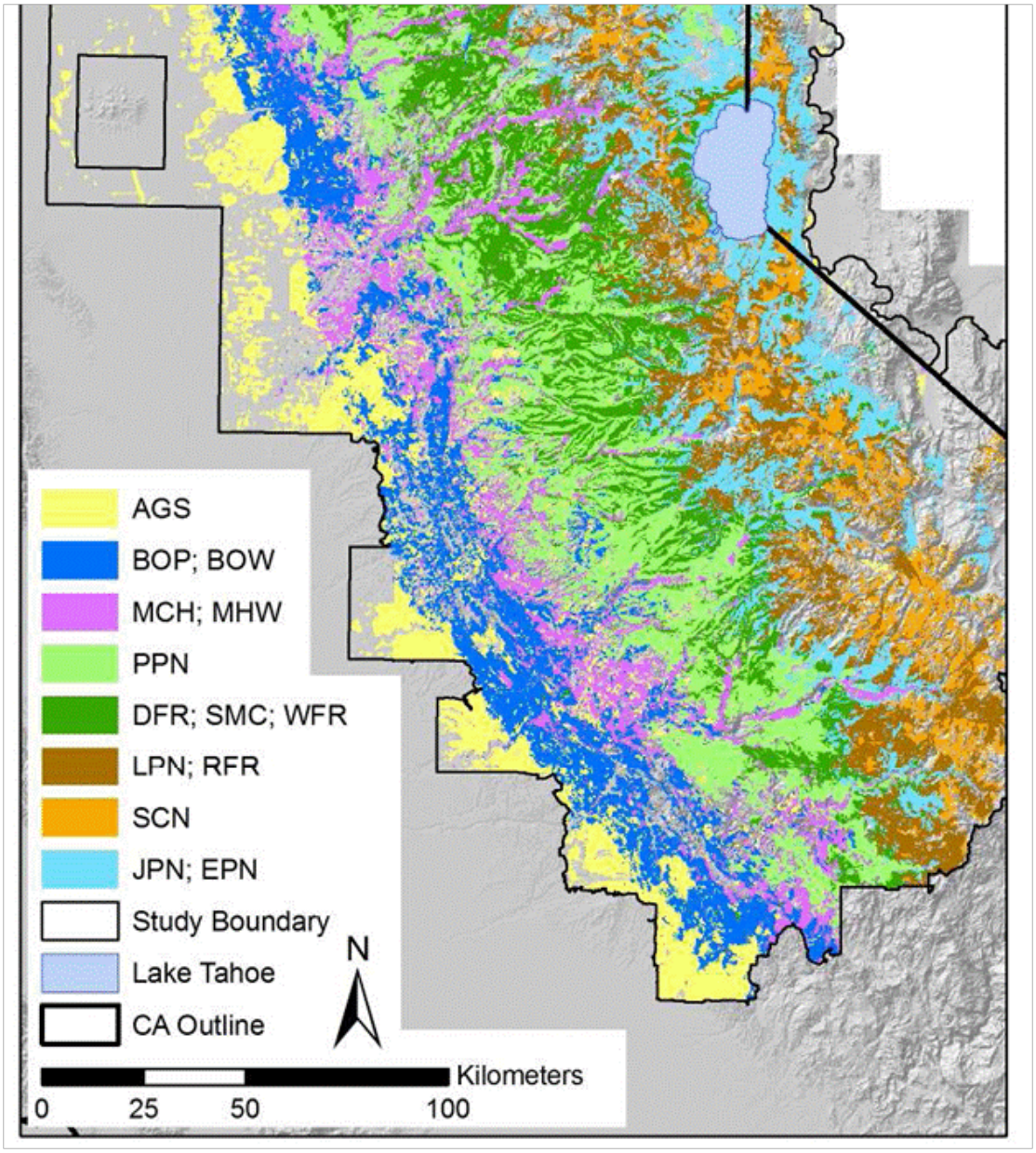


Figure 8(A) Distribution of major vegetation types in the central and northern Sierra Nevada in the period 1932-1936. Mapped by the US Forest Service "Wieslander" mapping project. Maps digitized and vegetation types cross-walked to CWHR type by UC-Davis Information Center for the Environment. AGS = agriculture; BOP = blue oak/foothill pine; BOW = blue oak woodland; MCH = mixed conifer hardwood; MHW = mixed hardwood; PPN = ponderosa pine; DFR = Douglas-fir; SMC = Sierra mixed conifer; WFR = white fir; LPN = lodgepole pine; RFR = red fir; SCN = Subalpine conifer; JPN = Jeffrey pine; EPN = eastside pine. The Stanislaus NF comprises the southern 1/3 of the mapped area.

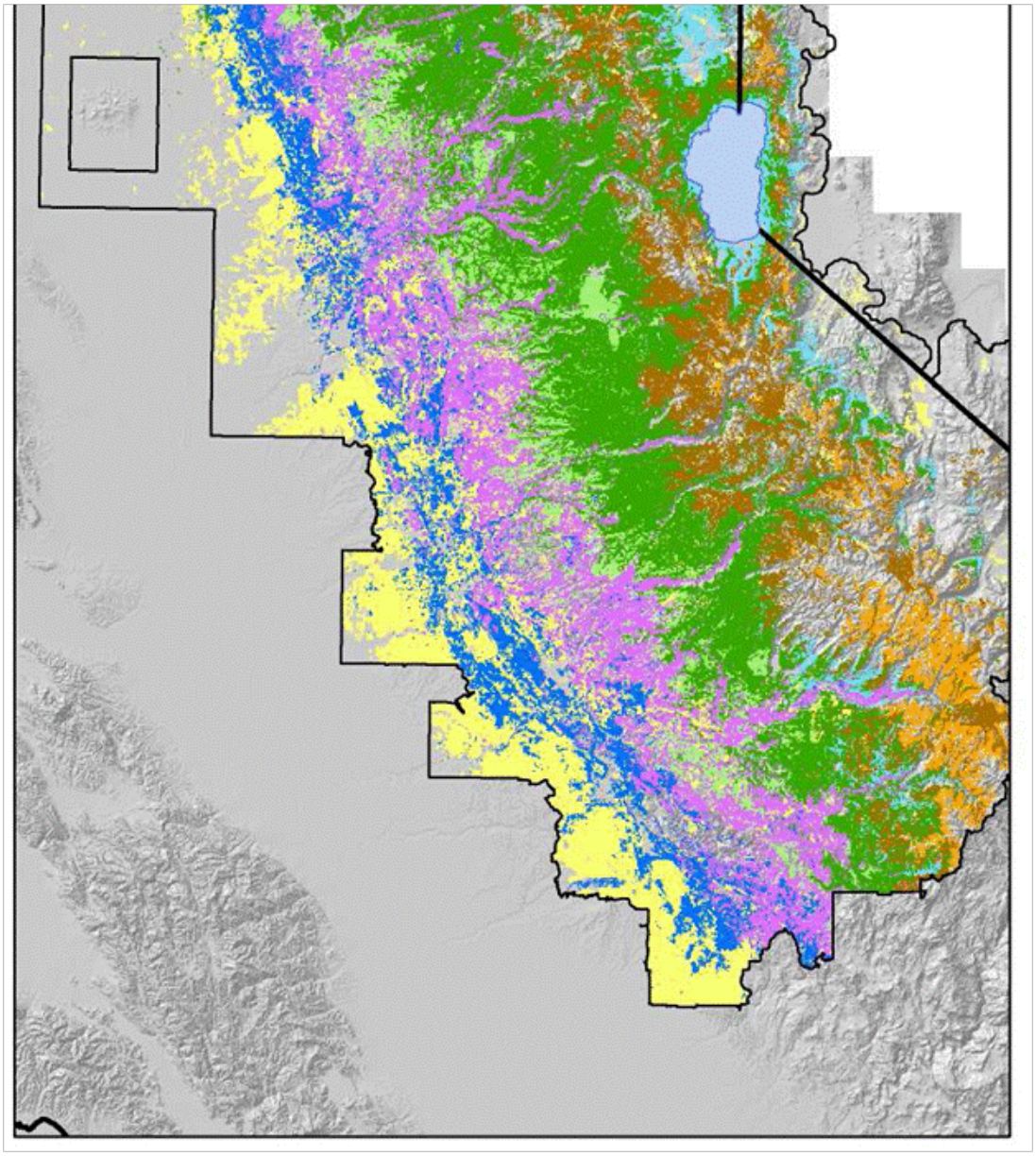


Figure 8(B) Distribution of major vegetation types in the central and northern Sierra Nevada in 2000. Mapped by the US Forest Service Pacific Southwest Region Remote Sensing Laboratory. See Fig. 7(A) for key and scale. The major patterns of change between 1934 and 2000 are: (1) loss of yellow pine (ponderosa and Jeffrey pine) dominated forest; (2) expansion of shade tolerant conifers (DFR, WFR, SMC); (3) loss of blue oak woodland; (4) increase in hardwood dominated forests; (5) loss of subalpine and alpine vegetation.

Wildlife

Changes in climate may have both direct (e.g. thermal stress) and indirect (e.g. changes in species interactions and vegetation) effects on wildlife distributions and abundances (Martin 2007; Rubidge et al. 2011). Direct effects of climate warming are predicted to force species upslope and to higher latitude, while indirect effects leave a more complex signature. Recent 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). Similar distribution patterns 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 Grinnell transects in the entire Sierra Nevada and concluded that 91% of species tracked changes in temperature or precipitation over time and 26% of species tracked both temperature and precipitation. While distributions of the American pika (*Ochotona collaris*) in the Sierra Nevada appear to be stable at present (Millar & Westfall 2010), pika distributions elsewhere appear to be moving upslope, as fast as 145 meters per decade (Beever et al. 2011), perhaps forecasting future threats to Sierra Nevada pika populations and highlighting the importance of Sierra Nevada refugia for this species. These studies suggest that wildlife are moving in response to changing climates in order to maintain environmental associations to which they are adapted. Species with a high degree of habitat specialization and a smaller natural thermal range are more sensitive to climate change than other species and may be under more pressure to move as climates warm (Gardali et al. 2012; Jiguet et al. 2006).

Indirect effects of climate change can have complex impacts on wildlife communities, resulting in shifting, stable, or collapsing ranges and abundances. In their study of small mammals, Moritz et al (2008) concluded that: (1) many species showed no change in their elevational range, (2) elevational range shifts resulted in minor changes in species richness and composition at varying spatial scales, and (3) closely-related species responded idiosyncratically to changes in climate and vegetation. Those species exhibiting range contraction or upward shifting are likely limited by thermal tolerance and contracting suitable vegetation distributions (e.g. *T. alpinus and T. senex*), while those with stable or expanding distributions (e.g. *T. speciosus*) may have been released from interspecific competition by retreating species (Rubidge et al. 2011). However, as shifting species' distributions create novel species assemblages, many species will also face new competition and/or predation pressures that may negatively impact them (Stralberg et al. 2009). As climate-sensitive ecosystem engineers and keystone species (e.g. American pika) are extirpated from thermally stressful sites, this may also dramatically alter ecosystem ability to support particular species and assemblages (Beever et al. 2011). Another major indirect impact of climate change on wildlife populations is the loss of synchrony between reproductive or migratory phenology and resource availability (Seavy et al. 2009, MacMynowski & Root 2007). Breeding dates of birds like tree swallows have advanced during the last century (e.g. up to 9 days, Dunn & Winkler 1999) which may lead to a mismatch in timing of egg laying relative to availability of food. Migration of California overwintering songbirds like Swainson's Thrush, Warbling Vireo, and Wilson's Warbler among others have also advanced significantly since 1969 (MacMynowski & Root 2007).

Indirect climate change impacts may also include changes to patterns in parasitism, disease, and disturbances that impact wildlife species. Moritz et al. (2008) concluded that in the Yosemite area most observed upwards range shifts for high-elevation species were consistent

with predicted climate warming, while changes in most lower- to mid-elevation species' ranges were more likely the result of landscape-level vegetation dynamics related primarily to fire history (Moritz et al. 2008). In other areas, decreasing songbird diversity and abundance has been indirectly attributed to decreasing snowfall patterns (Martin & Maron 2012). Low rates of snowfall allow for increased over-winter herbivory by ungulates like deer and elk, thus decreasing growth and abundance of some tree species (especially aspen and cottonwood), which may in turn decrease associated songbird abundances (Martin 2007; Martin & Maron 2012; Brodie et al. 2012). Drost and Fellers (1996) found that most frog and toad species in Yosemite exhibited widespread decline over the past several decades, regardless of elevation. Primary factors contributing to this faunal collapse throughout the Sierra Nevada include introduced predators, a fungal pathogen, pesticides, and climate change (Wake and Vredenburg 2008). The amount of food consumed by aquatic ectotherms (cold-blooded organisms) generally increases with temperature, so warmer water temperatures may be increasing predation rates by native and introduced predators on species like the yellow-legged frog in the Sierra Nevada (Rahel et al. 2008). Increased water temperatures also promote populations of parasites like copepods, which negatively affect the fitness of fish and amphibian species (Kupferberg et al. 2009). Species like the protected Foothill yellow-legged frog (*Rana boylii*) have been shown to suffer higher outbreaks of copepod parasites with increased water temperatures and drought-induced decreases in water flows in Northern California (Kupferberg *et al.* 2009).

III. Future predictions

Climate

As of today, no published climate change or vegetation change modeling has been carried out for the STF. Indeed, few future-climate modeling efforts have treated areas as restricted as the State of California. The principal limiting factor is the spatial scale of the General Circulation Models (GCMs) that are used to simulate future climate scenarios. Most GCMs produce raster outputs with pixels that are 10,000's of km^2 in area. To be used at finer scales, these outputs must be downscaled using a series of algorithms and assumptions – these finer-scale secondary products currently provide the most credible sources we have for estimating potential outcomes of long-term climate change for California. Another complication is the extent to which GCMs disagree with respect to the probable outcomes of climate change. For example, a recent comparison of 21 published GCM outputs that included California found that estimates of future precipitation ranged from a 26% increase per 1º C increase in temperature to an 8% decrease (Gutowski et al. 2000, Hakkarinen and Smith 2003). That said, there was some broad consensus: all of the reviewed GCMs predicted warming temperatures for California, and 13 of 21 predicted higher precipitation (three showed no change and five predicted decreases). According to Dettinger (2005), the most common prediction among the most recent models (which are considerably more complex and, ideally, more credible) is temperature warming by about 9° F by 2100, with precipitation remaining similar or slightly reduced compared to today. Most models agreed that summers will be drier than they are currently, regardless of levels of annual precipitation.

The most widely cited of the recent modeling efforts is probably Hayhoe et al. (2005). Hayhoe et al. (2005) used two contrasting GCMs (much warmer and wetter, vs. somewhat warmer and drier) under low and high greenhouse gas emissions scenarios to make projections of climate change impact for California over the next century. By 2100, under all GCM-emissions scenarios, April 1 snowpack was down by -22% to -93% in the 6,700-10,000 feet elevation belt, and the date of peak snowmelt was projected to occur from 3 to 24 days earlier in the season. Average temperatures were projected to increase by 2 to 4 °F in the winter and 4 to 8 degrees in the summer. Finally, three of the four GCM-emissions scenarios employed by Hayhoe et al. (2005) predicted strong decreases in annual precipitation by 2100, ranging from -91 to -157%; the remaining scenario predicted a 38% increase. Although the southern Sierra Nevada snowpack has generally remained steady (or risen) over the past half-century (Fig. 6; Moser et al. 2009), continued warming is likely to erode the temperature buffer that the high southern Sierra Nevada enjoys. Most modeling projects a continuously increasing rain:snow ratio and earlier runoff dates for the next century, with decreased snowpack (late winter snow accumulation decreases by 50% by 2100) and growing-season stream flow even in the higher elevation river basins (Miller et al. 2003, Moser et al. 2009).

Hydrology

Modeling future hydrological changes in California, Miller et al. (2003) found that annual streamflow volumes were strongly dependent on the precipitation scenario, but changes in seasonal runoff were more temperature dependent. Predicted spring and summer runoff was lower in all of the California river basins they modeled, except where precipitation was greatly increased, in which case runoff was unchanged from today (Miller et al. 2003). Runoff in the winter and early spring was predicted to be higher under most of the climate scenarios because higher temperatures cause snow to melt earlier. Flood potential in California rivers that are fed principally by snowmelt (i.e., higher elevation streams) was predicted to increase under all scenarios of climate change, principally due to earlier dates of peak daily flows and the increase in the proportion of precipitation falling as rain (Miller et al. 2003). Timing of peak flow may be expected to advance by up to seven weeks by 2100, depending on the climate scenario (Young et al. 2009).

Under the wettest climate scenario modeled by Miller et al. (2003), by 2100 the volume of flow during the highest flow days could more than double in many Sierra Nevada rivers, and the predicted increase in peak flow was most pronounced in higher elevation river basins, due to the greater reliance on snowmelt. Das et al. (2011) also found that under simulated future climate scenarios, all models predict greater flood magnitude and most predict greater flood frequency in both the Northern and Southern Sierra Nevada. 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 as evidenced by recent case studies (e.g., DeGraff et al. 2011, Huggel et al. 2012). Increased flood risk is thus a high probability outcome of the continuation of current climate change trends, because temperature, not precipitation, is the main driver of higher peak runoff (Miller et al. 2003). Increased flooding is not the only predicted result of seasonal shifts in peak flows and warming

temperatures. Warming temperatures are also expected to extend the period of summer drought, and decrease flow magnitude in the dry months (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 & Garen 2005), with significant economic, social, and biological impacts (Mote et al. 2005).

Vegetation

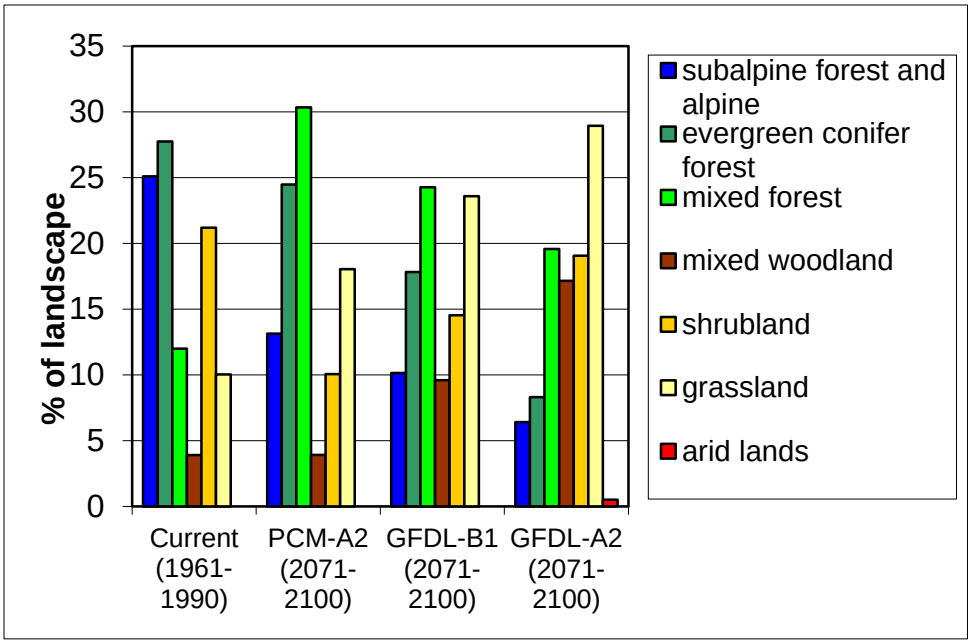
Lenihan et al. (2003, 2008) used a dynamic ecosystem model ("MC1") which estimates the distribution and the productivity of terrestrial ecosystems such as forests, grasslands, and deserts across a grid of 100 km^2 cells. To this date, this is the highest resolution at which a model of this kind has been applied in California, but it is not of high enough resolution to be applied to the SNF as a unit. Based on their modeling results, Lenihan et al. (2003, 2008) projected that forest types and other vegetation dominated by woody plants in California would migrate to higher elevations as warmer temperatures make those areas suitable for colonization and survival. For example, with higher temperatures and a longer growing season, the area occupied by subalpine and alpine vegetation was predicted to decrease as evergreen conifer forests and shrublands migrate to higher altitudes (Fig. 9). Under their "wetter" future scenarios (i.e., slightly wetter or similar to today), Lenihan et al. (2003, 2008) projected a general expansion of forests in the Sierra Nevada, especially north of the SNF and at higher elevations. With higher rainfall and higher nighttime minimum temperatures, broadleaf trees (especially oak species) were predicted to replace conifer-dominated forests in many parts of the low and middle elevation Sierra Nevada. Under their drier future scenarios, Lenihan et al. (2003, 2008) predicted that grasslands would expand, and that increases in the extent of tree-dominated vegetation would be minimal. An expansion of shrublands into conifer types was also predicted, due to drought and increases in fire frequency and severity (see below), but increasing fire frequency in the southern Sierra Nevada may replace much low to middle elevation shrubland with grassland (Fig. 9). Hayhoe et al. (2005) also used the MC1 ecosystem model to predict vegetation and ecosystem changes under a number of different future greenhouse gas emissions scenarios. Their results were qualitatively similar to the Lenihan et al. (2003, 2008) results. Ababneh and Woolfenden (2010) note that alpine meadows in the White Mountains may experience a shift in cover from wet meadow to dry meadow species, as well as encroachment by surrounding shrubs. Loarie et al. (2008) projected that 66% of California's native flora will experience >80% reduction in range size by 2100.

Fire

The combination of warmer climate with higher CO_2 fertilization will likely cause more frequent and more extensive fires throughout western North America (Price and Rind 1994, Flannigan et al. 2000); fire responds rapidly to changes in climate and will likely overshadow the direct effects of climate change on tree species distributions and migrations (Flannigan et al. 2000, Dale et al. 2001). A temporal pattern of climate-driven increases in fire activity is already apparent in the western United States (Westerling et al. 2006), and modeling studies specific to California expect increased fire activity to persist and possibly accelerate under most future climate scenarios, due to increased growth of fuels under higher CO_2 (and in some cases precipitation), decreased fuel moistures from warmer dry season temperatures, and possibly increased thundercell activity (Price and Rind 1994, Miller and Urban 1999, Lenihan et al. 2003,

2008; Westerling and Bryant 2006). Temperature has been shown to strongly influence fire frequency and area burned, and increased temperatures will lead to increased fire frequency and size (Guyette et al 2012, Spracklen et al. 2009). By 2100, Lenihan et al.'s (2003, 2008) simulations suggest a *c.* 5% to 8% increase in annual burned area across California, depending on the climate scenario (Fig. 10). Within the Western US, Spracklen et al (2009) found that the Pacific Northwest, including the Sierra Nevada and Cascade regions of California, showed the largest projected increase in area burned over the next half century. Within California, mid-elevation sites on the west side of the Sierras are likely to show the greatest increases in burned area in the next few decades (Westerling et al. 2011). Lutz et al. (2009) project that both the number of lightning ignited fires and the annual area burned at high severity in Yosemite National Park in the Sierra Nevada will increase by about 20% by 2020-2049 (19.1% and 21.9% respectively) due to projected decreases in snowpack. Westerling and Bryant (2008) predict a 10-35% increase in large fire risk by midcentury in California and Nevada. Increased frequencies and/or intensities of fire in coniferous forest in California will almost certainly drive changes in tree species compositions (Lenihan et al. 2003, 2008), and will likely reduce the size and extent of late-successional refugia (USFS and BLM 1994, McKenzie et al. 2004). Thus, if fire becomes more active under future climates, there may be significant repercussions for old growth forest and old growth-dependent flora and fauna.

A key question is to what extent future fire regimes in montane California will be characterized by either more or less severe fire than is currently (or was historically) the case. Fire regimes are driven principally by the effects of weather/climate and fuel type and availability (Bond and van Wilgen 1996). Seventy years of effective fire suppression in the semiarid American West have led to fuel-rich conditions that are conducive to intense forest fires that remove significant amounts of biomass (McKelvey et al. 1996, Arno and Fiedler 2005, Miller et al. 2009), and most future climate modeling predicts climatic conditions that will likely exacerbate these conditions. Basing their analysis on two GCMs under the conditions of doubled atmospheric CO2 and increased annual precipitation, Flannigan et al. (2000) predicted that mean fire severity in California (measured by difficulty of control) would increase by about 10% averaged across the state. Vegetation growth models that incorporate rising atmospheric CO2 show an expansion of woody vegetation on many western landscapes (Lenihan et al. 2003, 2008; Hayhoe et al. 2005), which could feedback into increased fuel biomass and connectivity and more intense (and thus more severe) fires. Use of paleoecological analogies also suggests that parts of the Pacific Northwest (including northern California) could experience more severe fire conditions under warmer, more CO2-rich climates (Whitlock et al., 2003). Fire frequency and severity (or size) are usually assumed to be inversely related (Pickett and White 1985), and a number of researchers have demonstrated this relationship for Sierra Nevada forests (e.g. Swetnam 1993, Miller and Urban 1999), but if fuels grow more rapidly and dry more rapidly – as is predicted under many future climate scenarios – then both severity and frequency may increase. In this scenario, profound vegetation type conversion is all but inevitable. Lenihan et al.'s (2003, 2008) results for fire intensity predict that large proportions of the Sierra Nevada landscape may see mean fire intensities increase over current conditions by the end of the century, with the actual change in intensity depending on future precipitation patterns.



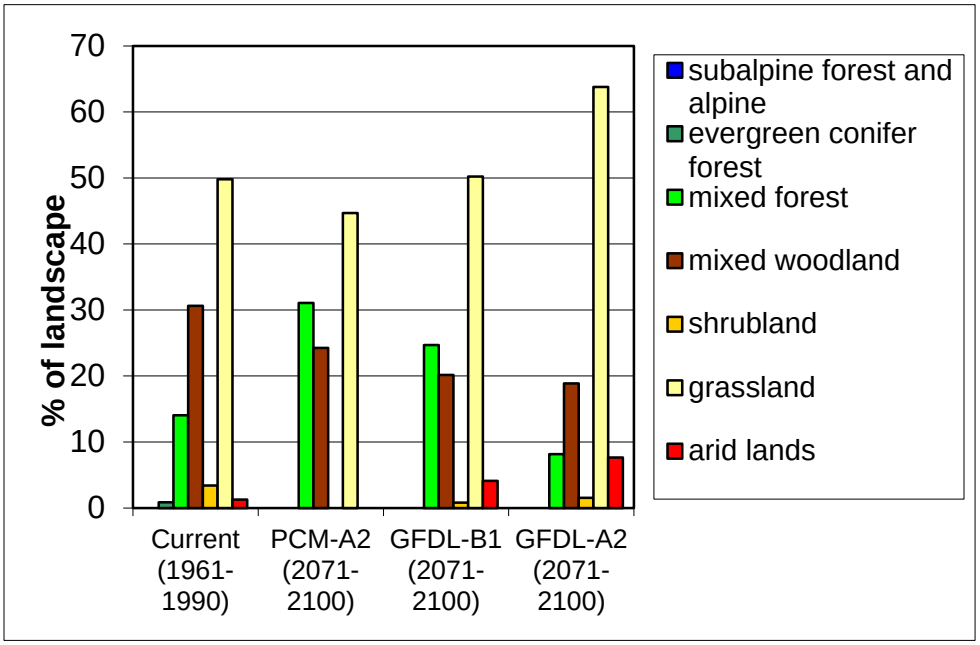


Figure 9. MC1 outputs for the Sierra Nevada and Sierra Nevada Foothills Ecological Sections, current vs. future projections of vegetation extent. These Ecological Sections include most of the Sierra Nevada west slope. The GFDL-B1 scenario = moderately drier than today, with a moderate temperature increase (<5.5° F); PCM-A2 = similar ppt. to today, with <5.5° temp. increase; GFDL-A2 = much drier than today and much warmer (>7.2° higher) All scenarios project significant loss of subalpine and alpine vegetation. Most scenarios project lower cover of shrubland (including west side chaparral and east side sagebrush), due principally to increasing frequencies and extent of fire. Large increases in the hardwood component of forests are projected in all scenarios except for the hot-dry scenario in the Foothills. Large increases in cover of grassland are projected for the Sierra Nevada section. The drier scenarios project moderate expansion of arid lands. In the Sierra Nevada section, conifer forest decreases in cover under all scenarios. From Lenihan et al. (2008).

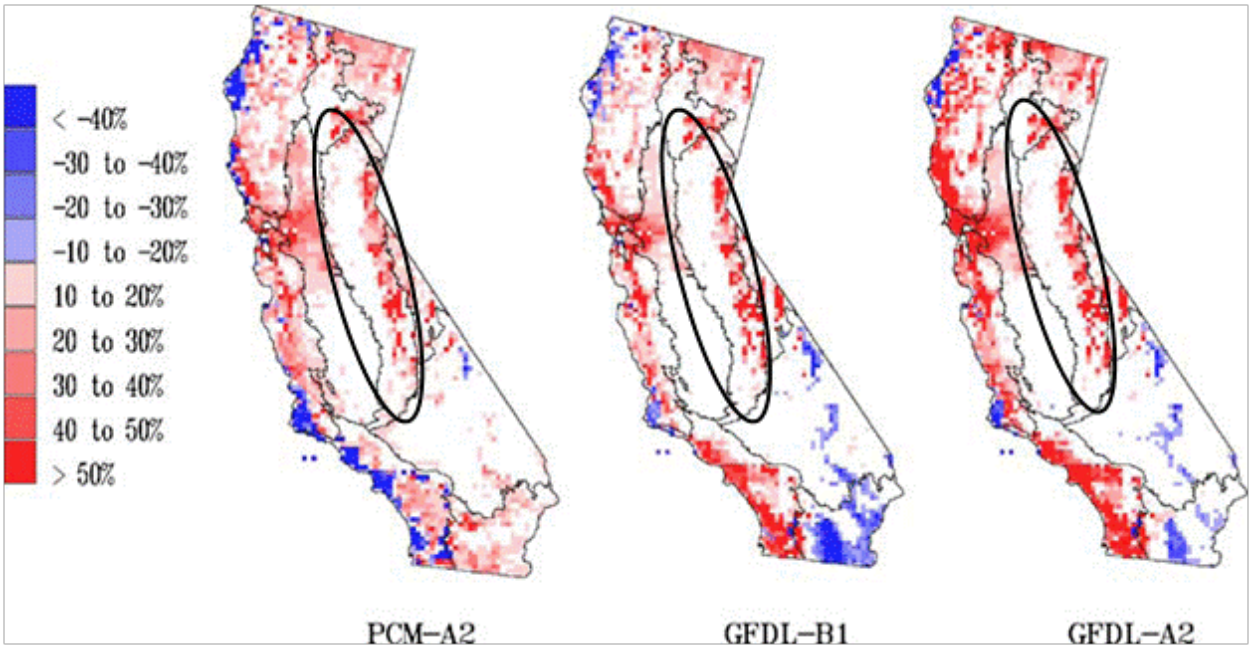


Figure 10. Percent change in projected mean annual area burned for the 2050-2099 period relative to the mean annual area burned for the historical period (1895-2003). Sierra Nevada is circled. Figure from Lenihan et al. (2008). See Fig. 13 for description of the climate and emissions scenarios (PCM-A2, GFDL-B1, GFDL-A2).

Wildlife

Significant changes in California's terrestrial fauna and flora are projected over the next century. Stralberg et al. (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. 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 were projected. Using species distribution modeling, the California Avian Data Center (2011) projected that approximately 60% of coniferous forest bird species in the Sierra Nevada will exhibit substantial range reductions within the next 40 to 90 years (using 21 focal avian species). A total of 128 out of 358 (36%) of California's bird species of "special concern" (rare, threatened, endangered, or experiencing significant decline; Shuford & Gardali 2008) were ranked as vulnerable to climate change, especially 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. (2009a,b) projected high vulnerability of California's amphibian fauna and moderate vulnerability of California's mammalian fauna under a high greenhouse gas emissions scenario by the end of the century; Lawler et al. projected >50% change in the amphibian fauna and 10-40% change in the mammalian fauna.

Direct effects will continue to impacts wildlife species in the future, likely at an accelerating pace. Lawler et al (2012) investigated the possible effects of climate change on selected species of the genus *Martes* and found that macroclimate conditions closely correlated with Pacific fisher (*Martes pennanti*) presence in California were likely to change greatly over the next century, resulting in a possibly pronounced loss of suitable habitat. Their results suggested that

martens and fishers will be highly sensitive to climate change, and would probably experience the largest climate impacts at their southernmost latitudes (i.e. in the southern Sierra Nevada). When combined with other stressors, predicted climate changes represent significant threats to aquatic communities (Schindler 1997). Diminished flow magnitude is one of the most important predictors of biological integrity of fish and macroinvertebrate communities (Carlisle et al. 2010). Where compounded with human-induced disturbance, increased flooding may negatively impact some aquatic communities (Herbst & Cooper 2010). Additionally, as air temperatures rise, water temperatures are expected to continue to warm as well, potentially resulting in local species extirpations, increased non-native species invasions, declines in macroinvertebrate communities, and temporal disruptions to spawning and larval life stages (Kaushal et al 2010; Viers & Rheinheimer 2011). Those aquatic species with a competitive advantage in colder waters will also likely suffer losses due to both thermal stress and increased competition as water temperatures rise (Rahel et al. 2008; Kennedy et al. 2009). Salmonids may be particularly sensitive to warming water temperatures (ISAB 2007) and in the Sierra Nevada, increases in water temperatures will likely reduce ranges for thermally sensitive species like rainbow trout, as physiological limitations eliminate low-elevation habitat options and natural topographic barriers limit dispersal to higher elevation waters (Viers & Rheinheimer 2011).

Indirect effects will also continue to impact wildlife species in complex ways in the future. Species that require older, denser, and more structurally complex forest conditions, like Sierra Nevada Fisher and the Spotted Owl, will likely be negatively impacted by changes in fire regimes associated with climate change (Scheller et al. 2011). Lawler et al. (2012) noted that fisher habitat is driven to a great extent by local vegetation features and thus the authors examined stand-level implications of fire under a series of future fire scenarios, since fire occurrence and behavior, largely driven by climate/weather, have substantial effects on local vegetation. They recommended protecting fisher habitat through targeted forest-fuel treatment, and applying more liberal fire-management policies to naturally ignited fires during moderate weather conditions. Sensitive benthic invertebrate populations may also be reduced by increases in large and severe wildfires that are likely to be associated with climate warming (Oliver *et al.* 2012). Larger effects will likely be observed in small, first-order streams (Oliver et al. 2012). Some fish species in the Sierra Nevada, like the non-native brook trout, will likely decline in abundance due to alterations in frequency, intensity, and seasonal timing of floods in areas like Sagehen Creek, while other species like rainbow trout may subsequently benefit from decreased competition (Meyers et al. 2010).

Loarie et al. (2008) identified the southern Sierra Nevada and the coastal mountains of Northwest California as climate change refugia, defined as areas projected to sustain species with otherwise shrinking ranges. Authors like Loarie et al. (2008) and Lawler et al. (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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