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

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I. Local trends in climate over the past century

The data presented in this section are derived primarily from two weather stations with long-term meteorological records from the general area of the Sierra National Forest ("SNF"). The second-longest quasi-continuous weather record is provided by the Huntington Lake station (1915-2009; WRCC 2010), which is within the approximate center of the SNF, and lies at 7020 feet above sea level (2830 m), at approximately 37º 13.76' N, 119º 14.63' W. The elevation of the station and surrounding vegetation are representative of the area of the SNF within which management activities are proposed. The Huntington Lake weather record is missing annual temperature data from the years 1915, 1948, 2003, and 2009, and precipitation data are missing from 1962-1974 (WRCC 2010). A 70-year dataset (1940-2009) is available from the Grants Grove station in Sequoia-Kings Canyon National Parks ("SEKI-NP") (6580 feet asl; 36º 44.2' N, 118º 57.8' W), which is found approximately 8 miles south of the southern boundary of the SNF (WRCC 2010). The SEKI-NP is missing annual temperature and precipitation data for 1940 and 1948. A 101-year dataset (1907-2007) is also available from the Yosemite National Park Headquarters Station in Yosemite Valley ("YOSE-NP") (4000 feet asl; 37º 45.0' N, 119º 35.0' W), which is near the northern boundary of SNF approximately 12 miles east of the YOSE-NP/SNF boundary. The YOSE-NP weather record is missing annual temperature data from year 1980 and annual precipitation data from the years 1923 and 1980 (WRCC 2010).

Temperature

Over the last 94 years, mean annual temperature at the Huntington Lake station has risen by about 1.8º Fahrenheit (Fig. 1; values from regression equation). This trend is driven by a highly significant increase in mean minimum (i.e., nighttime) temperatures, which have risen by 4º F since 1915. At the beginning of the record, the annual average of the monthly mean minima was below the freezing point, but it is now more than three degrees above the freezing point (Fig. 1). The 70-year record from Grants Grove shows a similar story, but with even more pronounced warming (Fig. 2). Mean annual temperatures at Grants Grove have risen by about 2.7º F since 1940, and nighttime mean minima have risen by about 5º F; the mean maxima have not changed. Similarly in Yosemite Valley, the mean annual temperature over a 101-year record increased by about 3.7°F since 1907, nighttime mean minima have risen by about 7.5° F, and the mean maxima did not change (Fig. 3). The occurrence of nighttime freezing temperatures has been decreasing over the last century. For example, at the beginning of the Huntington Lake data record six to seven months in a year could be expected to have average nighttime temperatures that fell below freezing. Today the average is closer to five months, and the trend is strongly downward (Fig. 4). A similar trend has been observed in Yosemite Valley, where average nighttime temperatures below freezing declined from 5.8 months a year to 3 months a year (Fig. 5).

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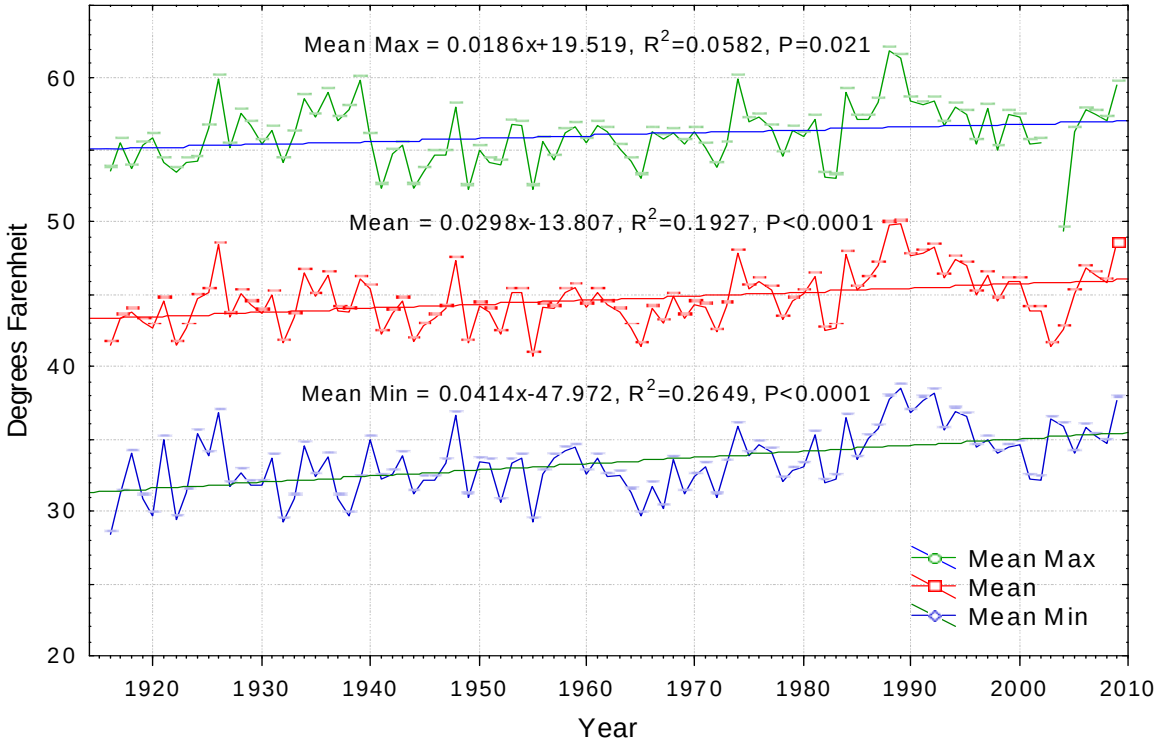

Figure 1. Annual mean, mean maximum, and mean minimum temperatures at Huntington Lake, California, 1915-2009. Trend lines fit with simple linear regression, no transformations employed. Data from WRCC 2010.

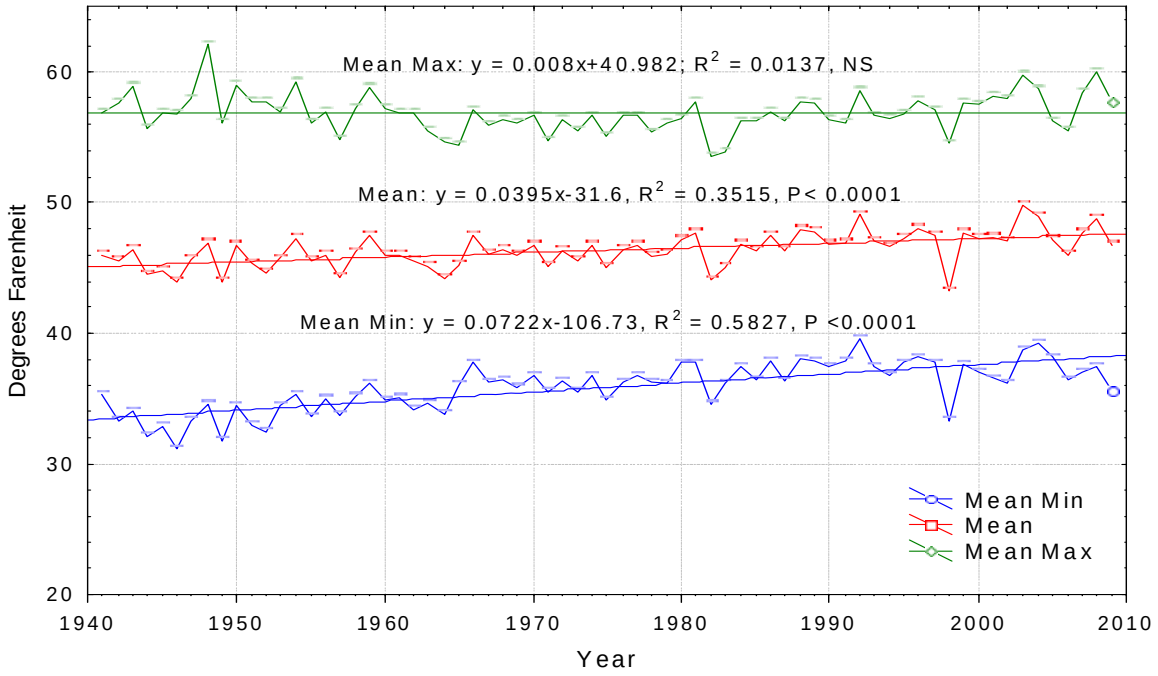

Figure 2. Annual mean, mean maximum, and mean minimum temperatures at Grants Grove, California, 1940-2009. Trend lines fit with simple linear regression, no transformations employed. Data from WRCC 2010.

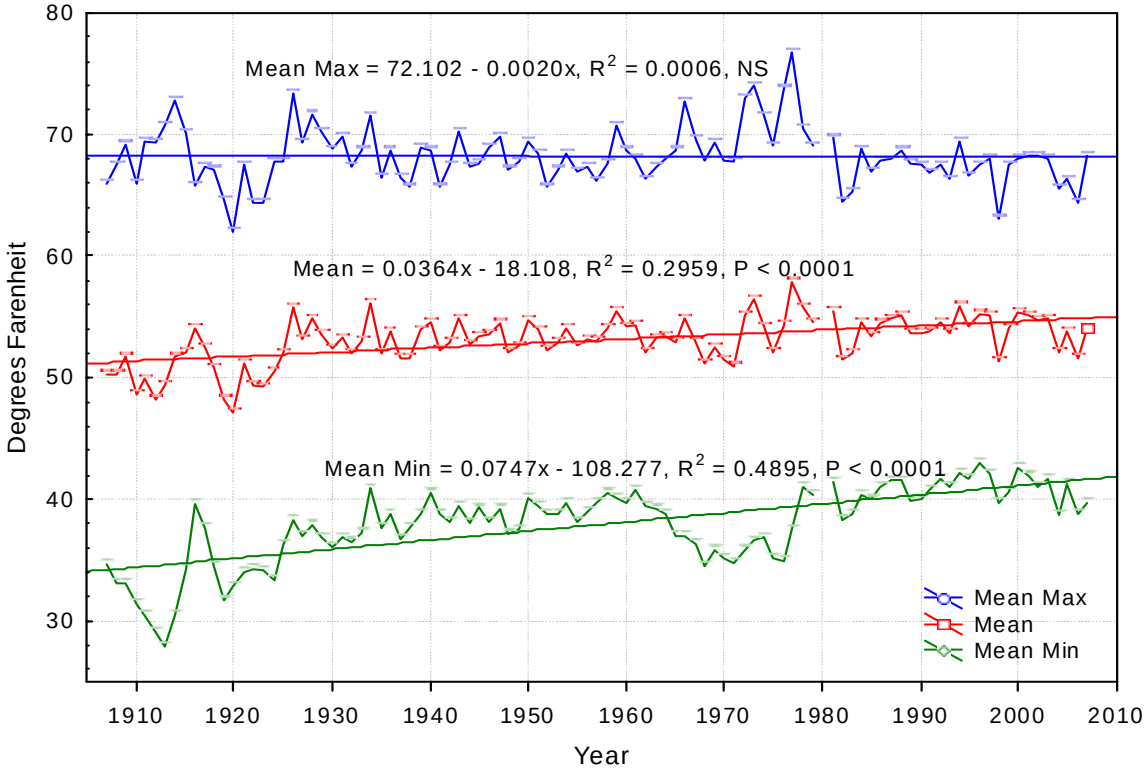

Figure 3. Annual mean, mean maximum, and mean minimum temperatures at Yosemite National Park in Yosemite Valley, California, 1907-2007. Trend lines fit with simple linear regression, no transformations employed. Data from WRCC 2010.

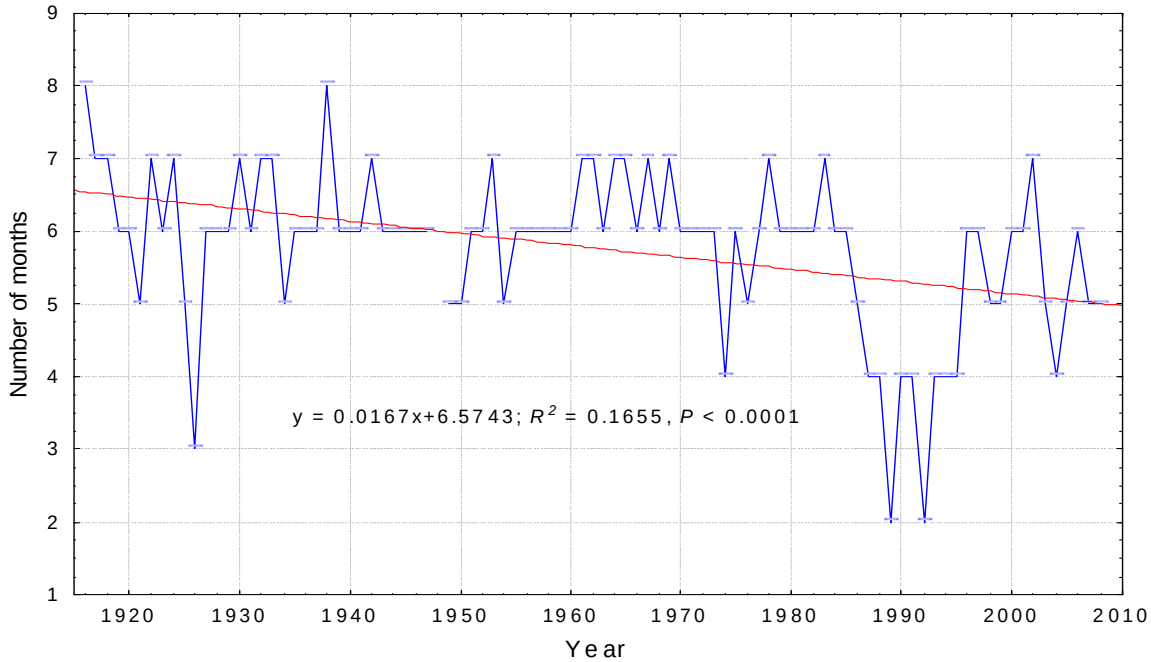

Figure 4. Number of months with the monthly mean minimum temperature remaining below freezing at Huntington Lake, California, 1915-2009. Trend line fit with simple linear regression. Data from WRCC 2010.

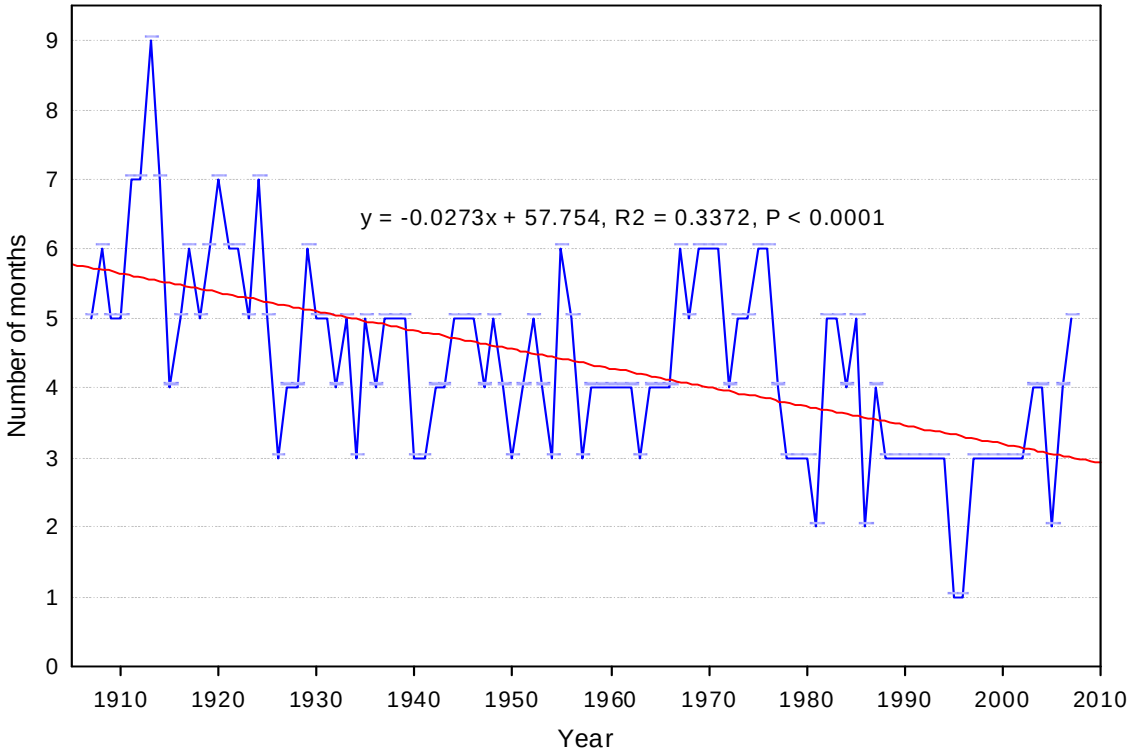

Figure 5. Number of months with the monthly mean minimum temperature remaining below freezing at Yosemite Valley, 1907-2007. Trend line fit with simple linear regression. Data from WRCC 2010.

Precipitation

Local and subregional precipitation trends in the Sierra Nevada range from negative to positive (WRCC 2010), and trends at even nearby stations can vary widely. The 94-year trend in precipitation at Huntington Lake is shown in Fig. 6. Average annual precipitation has risen greatly over the period (from a predicted 25.6 inches per year in 1915 to 45.6 inches per year in 2009), but there is very high interannual variability, such that the value predicted by the regression line in Fig. 6 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 number of extreme precipitation years, such as 1982, 1983, and 1996. In contrast to the Huntington Lake station, the Grants Grove station in SEKI-NP shows no statistically discernable change in mean annual precipitation between 1940 and 2009 (Fig. 7). However, the 101-year trend in precipitation at Yosemite Valley shows an 11-inch increase in annual precipitation over the past century (Fig. 8).

As is the case with precipitation itself, interannual variability in precipitation varies from station to station. At Huntington Lake, the 5-yr coefficient of variation for annual precipitation is rising strongly over time (Fig. 9), which demonstrates that year-to-year variability in precipitation has increased over the course of the last century. Further evidence of high variability in recent annual precipitation sums can be seen in the last thirty years of records from Huntington Lake: 13 of the 20 wettest years have occurred since 1980 and the 10 wettest have all occurred since 1978, but 2007 and 2009 were among the five driest years on record (2009 has incomplete data in the station record and is not shown in Fig. 9). Although increasing interannual variability has been documented for many Sierra Nevada weather stations, the Grants Grove station showed no long-term change between 1940 and 2009 at the Grants Grove station, and Yosemite Valley actually showed a slight decrease due to high variation between 1907 and 1927 (not shown; WRCC 2010).

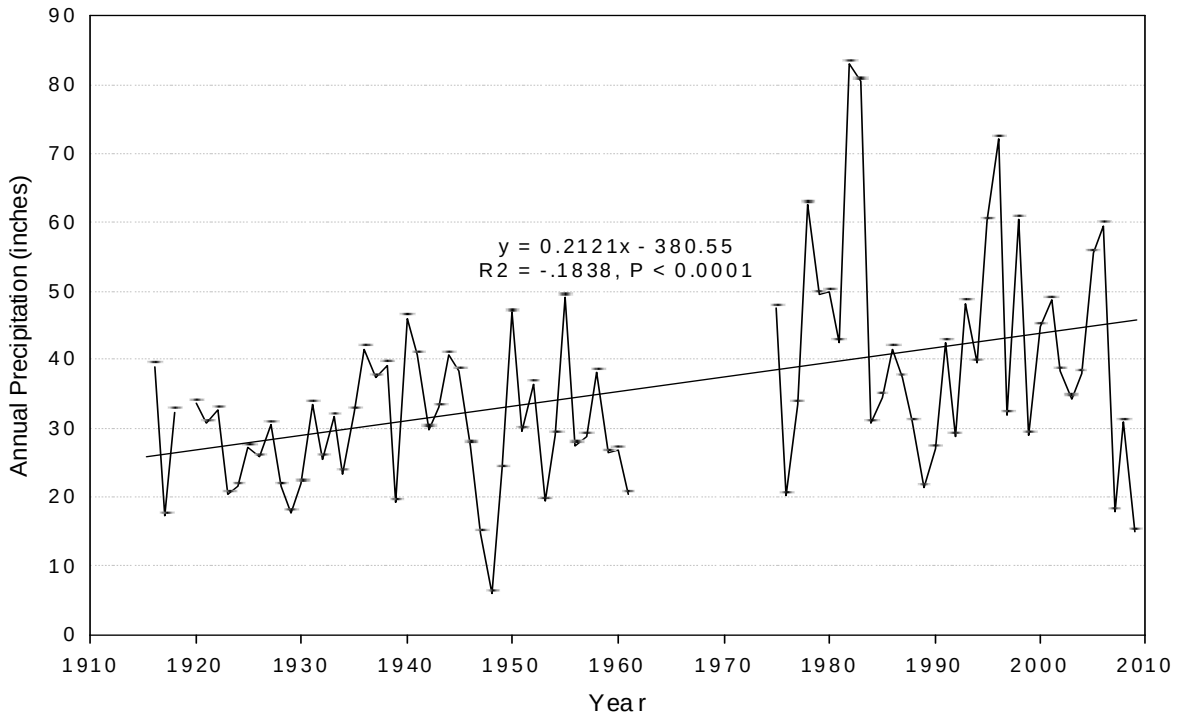

Figure 6. Mean annual precipitation at Huntington Lake, California, 1915-2009. Trendline fit with simple linear regression, no transformations employed. Data from WRCC 2010.

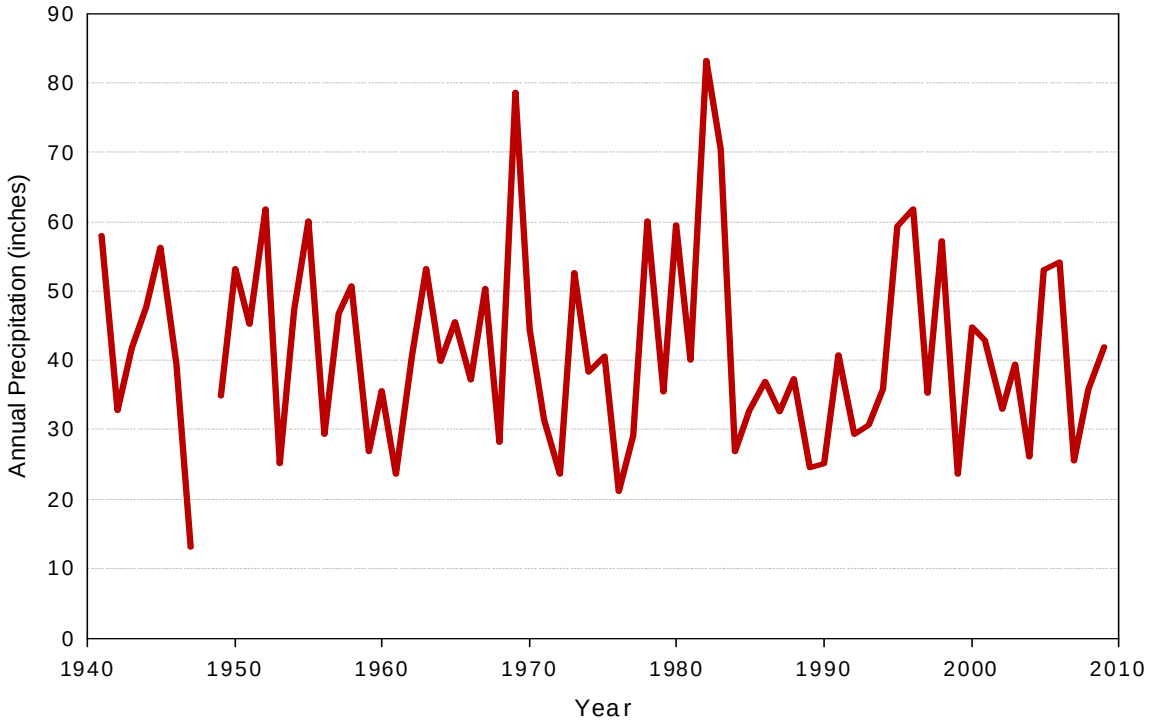

Figure 7. Mean annual precipitation at Grants Grove, California, 1940-2009. There is no statistically significant trend in the time series. Data from WRCC 2010.

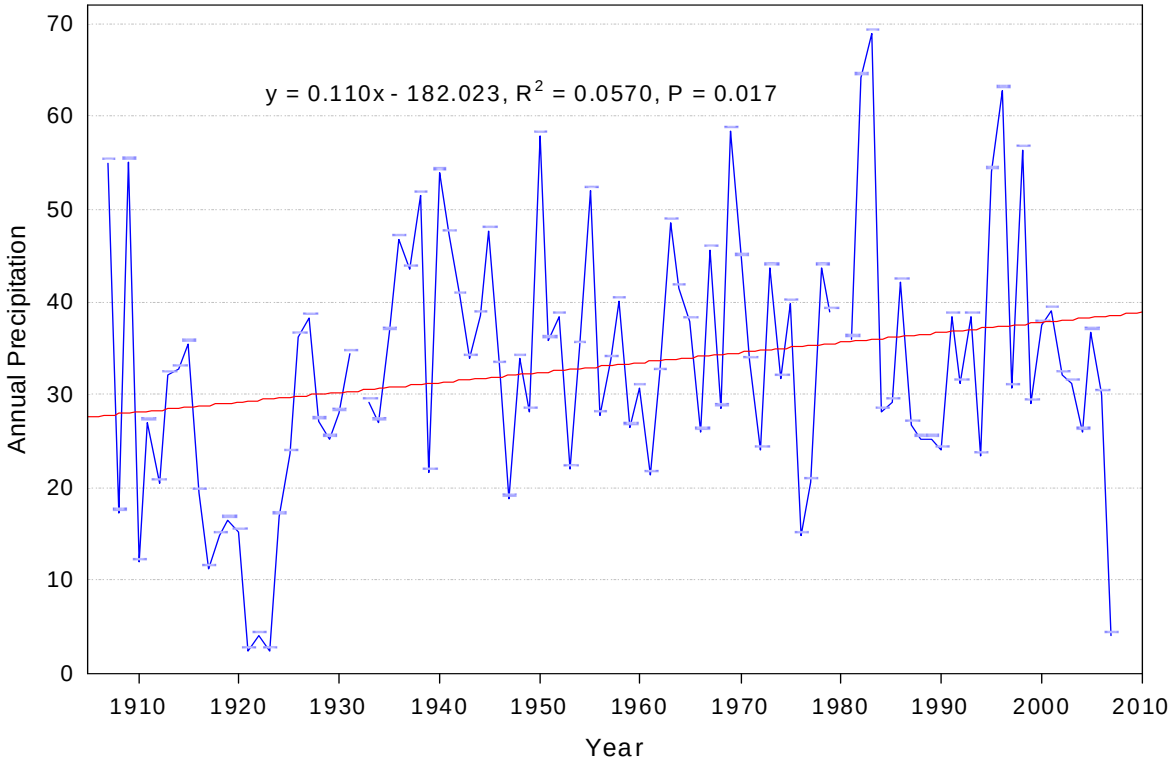

Figure 8. Mean annual precipitation at Yosemite Valley, California, 1907-2007. Trendline fit with simple linear regression, no transformations employed. Data from WRCC 2010.

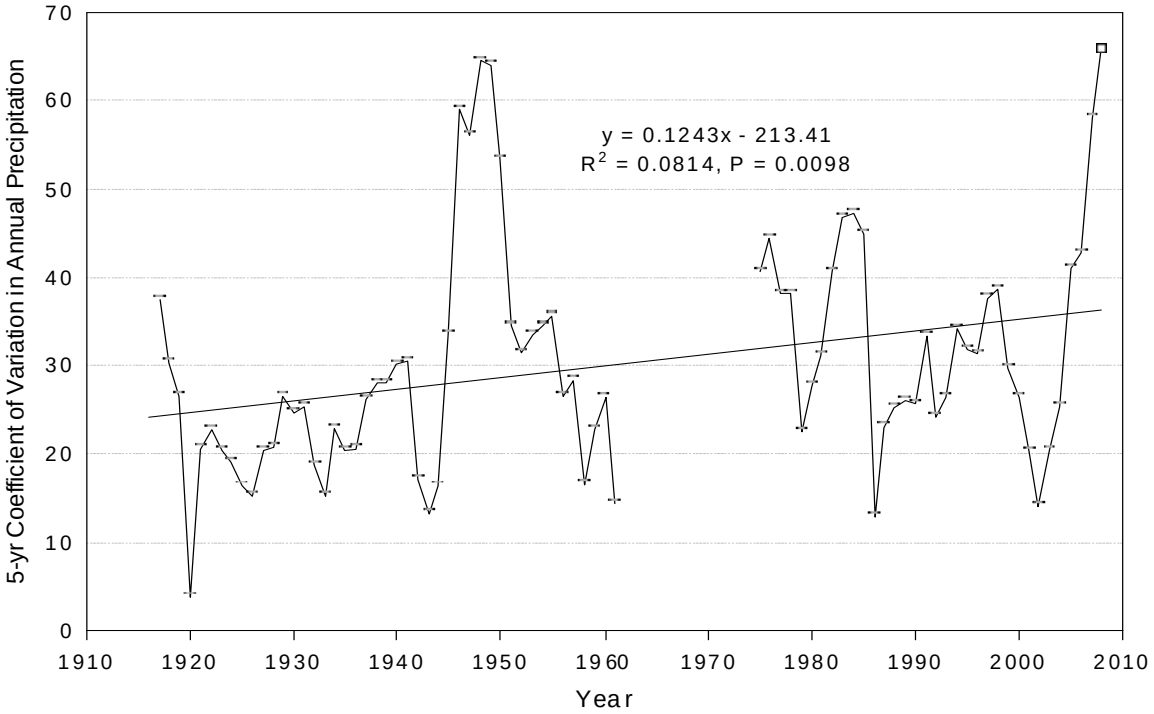

Figure 9. Five-year coefficients of variation in annual precipitation at Huntington Lake, California, 1915-2009. Data from WRCC 2010.

Because the southern Sierra Nevada is so high, the diminishing snowpack and snowwater equivalent trends seen across the rest of California have not yet occurred in many higher elevation river basins (Fig. 10). Like precipitation in general however, there are great differences in snowfall trends between different southern Sierra Nevada sites. For example, between 1915 and 1973 mean annual snowfall at Huntington Lake rose from around 200 inches to over 250 inches (predicted from linear regression, $R^2 = 0.065$, $P < 0.01$; WRCC 2010) (the record for snowfall from Huntington Lake is incomplete and ends in 1972), while the record from Grants Grove (1940-2009) and Lodgepole (1968- 2009) in SEKI-NP show no statistical trends in annual snowfall totals (WRCC 2010). Using time-series reconstruction, Christy and Hnilo (2010) observed a marginally positive but insignificant increase in snowpack at Huntington Lake during the past 95 years.

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

Hydrology

Stewart et al. (2005) showed that the onset of spring thaw in most major streams in the central Sierra Nevada occurred 5-30 days earlier in 2002 than in 1948, and peak streamflow (measured as the center of mass annual flow) occurred 5-15 days earlier. During the same period, March flows in the studied streams were mostly higher by 5- 20%, but June flows were mostly lower by the same amount; overall spring and early summer streamflow was down in most studied streams. Rising winter and spring temperatures appear to be the primary driver of these patterns (Stewart et al. 2005).

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. Miller et al. (2009) also showed that forest fire severity (a measure of the effect of fire on vegetation) rose strongly during the period 1984-2007, with the pattern centered in middle elevation conifer forests. 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.

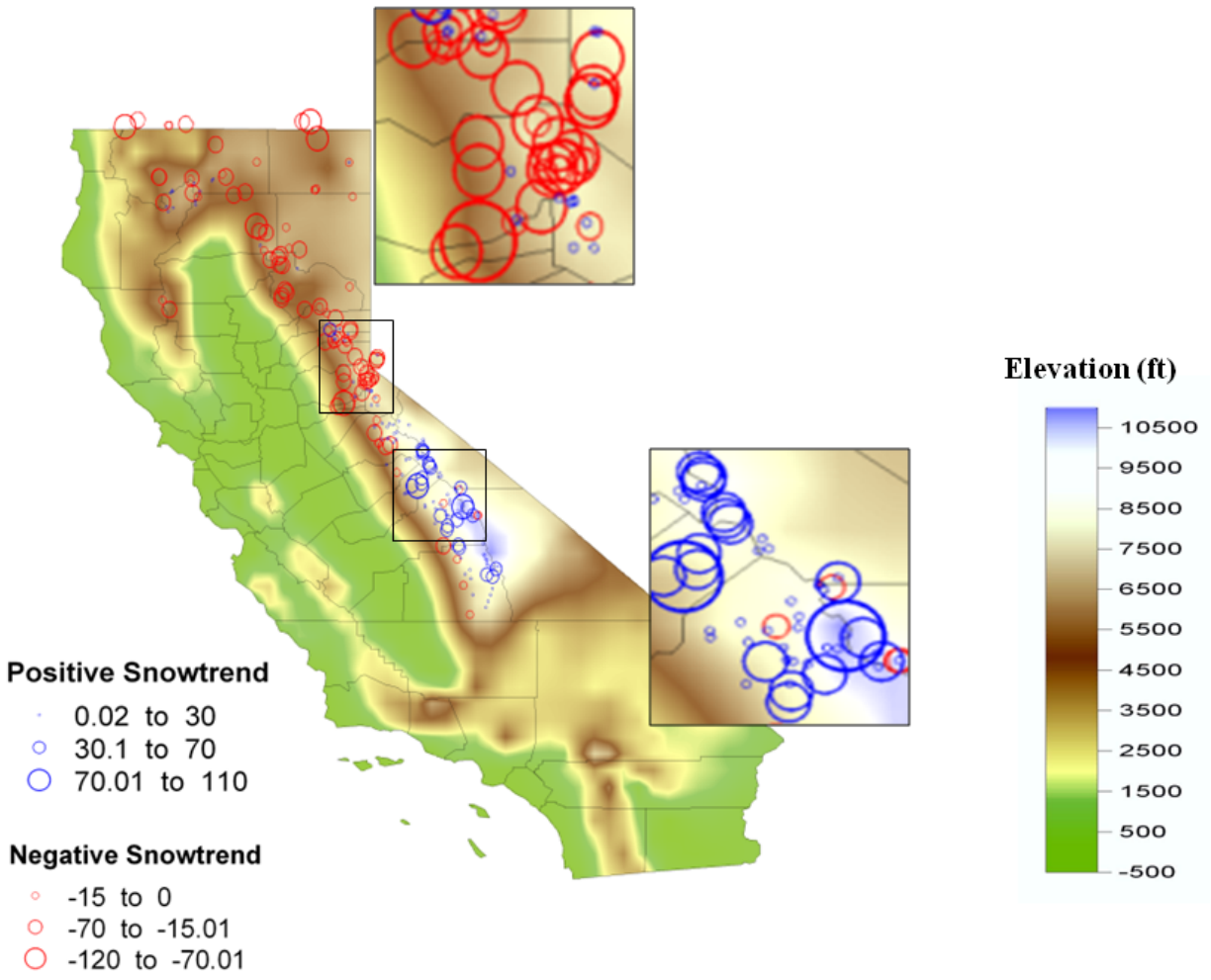

Figure 10. Trends in the amount of water contained in the snowpack ("snow water equivalent") on April 1, for the period 1950-1997. Red circles indicate percent decrease in snow water, blue circles indicate increase in snow water. From Moser et al. (2009).

Forest 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 higher precipitation in some cases) is actually making conditions better for some tree species in this stressful environment.

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. 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. 11a, 11b; 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.

Wildlife

Between 1914 and 1920, the Museum of Vertebrate Zoology (MVZ) at the University of California Berkeley surveyed the terrestrial vertebrate fauna at 41 sites along a transect that extended from the western slope of Yosemite National Park to an area near Mono Lake (Grinnell and Storer 1924). In the past decade, MVZ resurveyed the Yosemite transect to evaluate the near century-long changes in Yosemite's vertebrate fauna across this elevation gradient, stretching across numerous vegetation types (Mortiz 2007, Moritz et al. 2008). By comparing earlier and recent MVZ small mammal surveys, Moritz et al. (2008) 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, (3) many

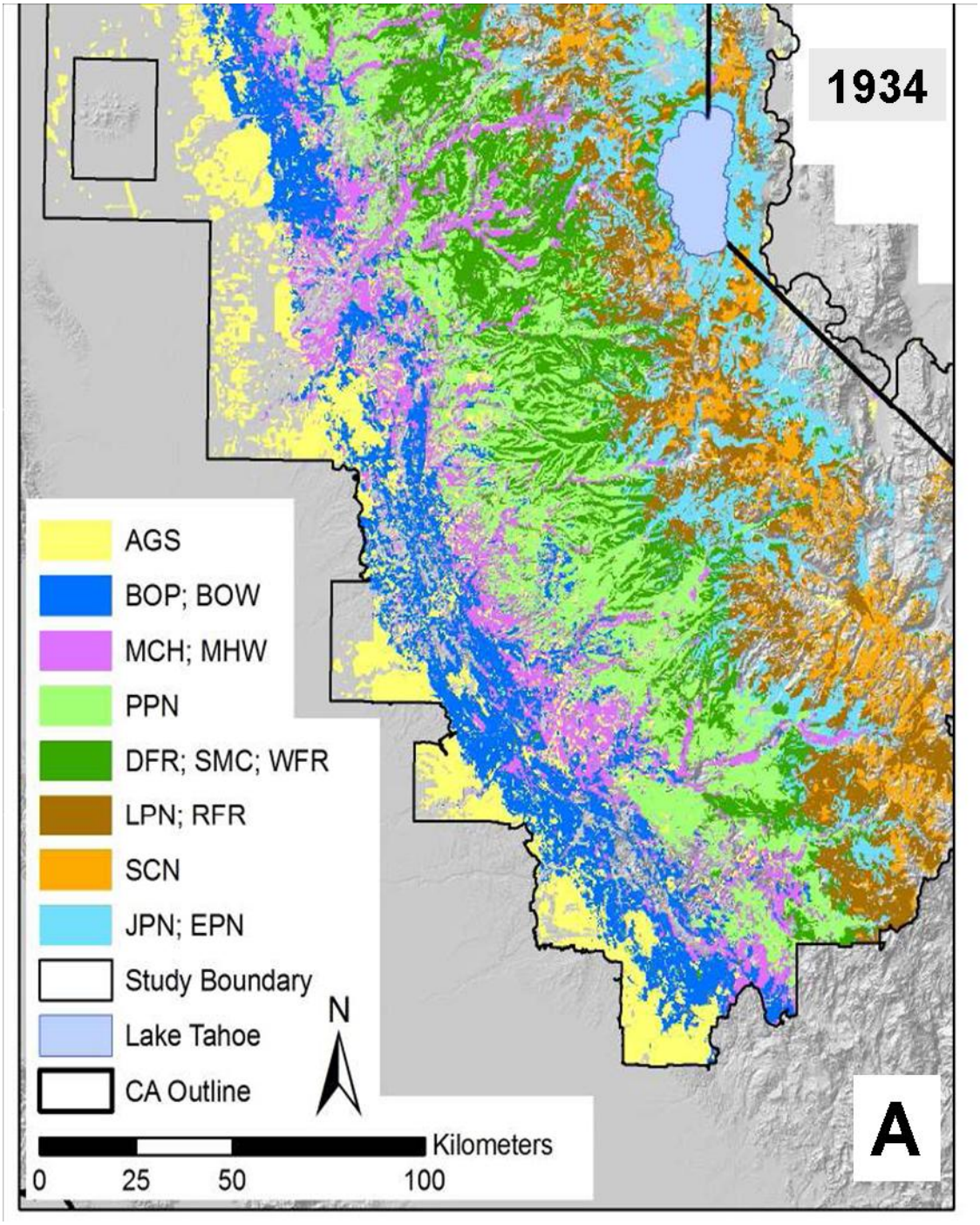

Figure 11. (A) Distribution of major vegetation types in the central and northern Sierra Nevada in the period 1932-1936. Mapped by the US Forest Service "Wieslander" mapping project. Maps digitized and vegetation types cross-walked to CWHR type by UC-Davis Information Center for the Environment. AGS = 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. Sierra National Forest is located just south of the mapped area, in and around the letter "A".

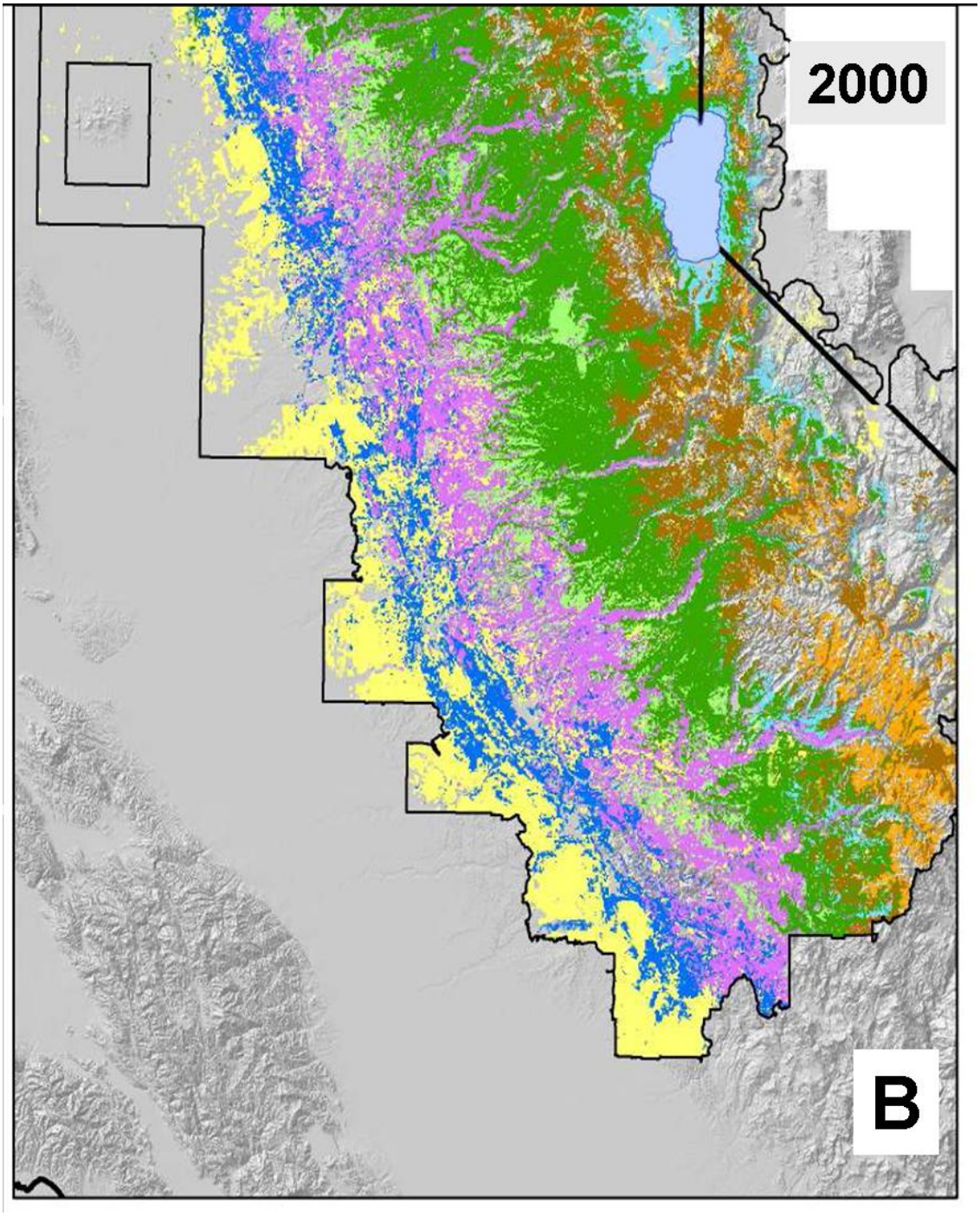

Figure 11. (B) Distribution of major vegetation types in the central and northern Sierra Nevada in 2000. Mapped by the US Forest Service Pacific Southwest Region Remote Sensing Laboratory. See Fig. IIi (A) for key and scale. The major patterns of change between 1934 and 2000 are: (1) loss of yellow pine (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. Sierra National Forest is located just south of the mapped area, in and around the letter “B”.

species showed no change in their elevational range, (4) elevational range shifts resulted in minor changes in species richness and composition at varying spatial scales, (5) closely-related species responded idiosyncratically to changes in climate and vegetation, and (6) most upwards range shifts for high-elevation species is consistent with predicted climate warming, but changes in most lower- to mid-elevation species' ranges are likely the result of landscape-level vegetation dynamics related primarily to fire history.

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 upwards 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. This suggests that birds move in response to changing climates in order to maintain environmental associations to which they are adapted. The authors also suggest that combining climate and niche models may be useful for predicting future changes in regional bird distributions (Tingley et al. 2009). In contrast with other faunal studies, 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).

III. Future predictions

Climate

As of today, no published climate change or vegetation change modeling has been carried out for the SNF. 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. 10; 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

Miller et al. (2003) modeled future hydrological changes in California as a function of two contrasting GCMs (the same GCMs used in Hayhoe et al. [2005] and Lenihan et al. [2003; see below]) and a variety of scenarios intermediate to the GCMs. Miller et al. (2003) found that annual streamflow volumes were strongly dependent on the precipitation scenario, but changes in seasonal runoff were more complex. 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. These increases in peak daily flows are predicted under all climate change scenarios, including those assuming reduced precipitation (Miller et al. 2003). The predicted increase in peak flow was most pronounced in higher elevation river basins, due to the greater reliance on snowmelt. If precipitation does increase, streamflow volumes during peak runoff could greatly increase. 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. This would result in a substantial increase in flood risk in flood-prone areas in the Central Valley. According to Miller et al. (2003), increased flood risk is a high probability outcome of the continuation of current climate change trends, because temperature, not precipitation, is the main driver of higher peak runoff. If climate change leads not only to an increase in average precipitation but also a shift to more extreme precipitation, then peak flows would be expected to increase even more.

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. 12). 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. 12). 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.

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). 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. 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 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 CO_2 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.

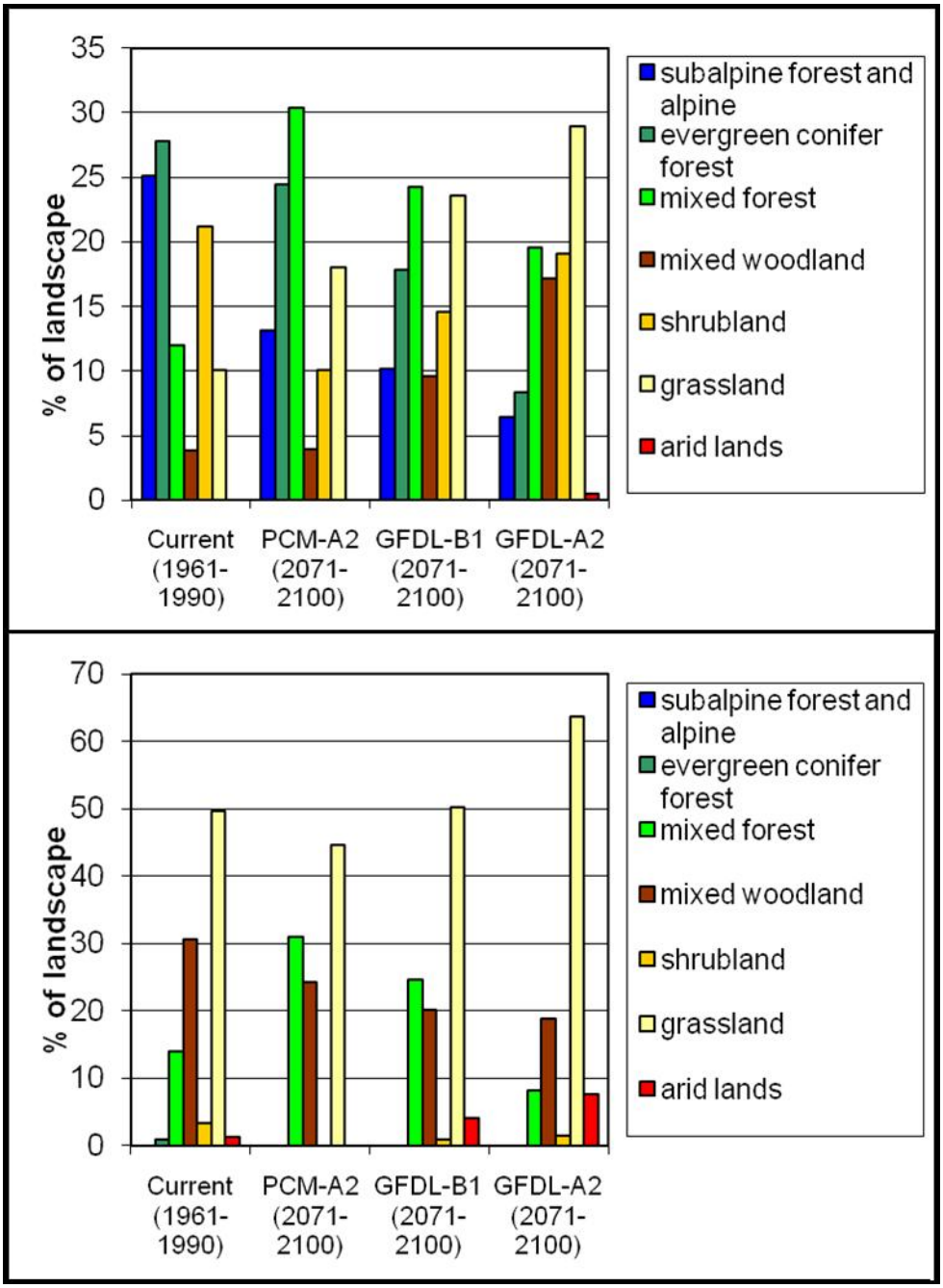

Figure 12. MC1 outputs for the Sierra Nevada and SN Foothills Ecological Sections, current vs. future projections of vegetation extent. These Ecological Sections include most of the Sierra Nevada west slope. The GFDL-B1 scenario = moderately drier than today, with a moderate temperature increase (<5.5º F); PCM-A2 = similar ppt. to today, with <5.5º temp. increase; GFDL-A2 = much drier than today and much warmer (>7.2º 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).

Vegetation growth models that incorporate rising atmospheric CO_2 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 CO_2-rich climates (Whitlock et al., 2003). Fire frequency and severity (or size) are usually assumed to be inversely related (Pickett and White 1985), and a number of researchers have demonstrated this relationship for 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 (Fig. 13).

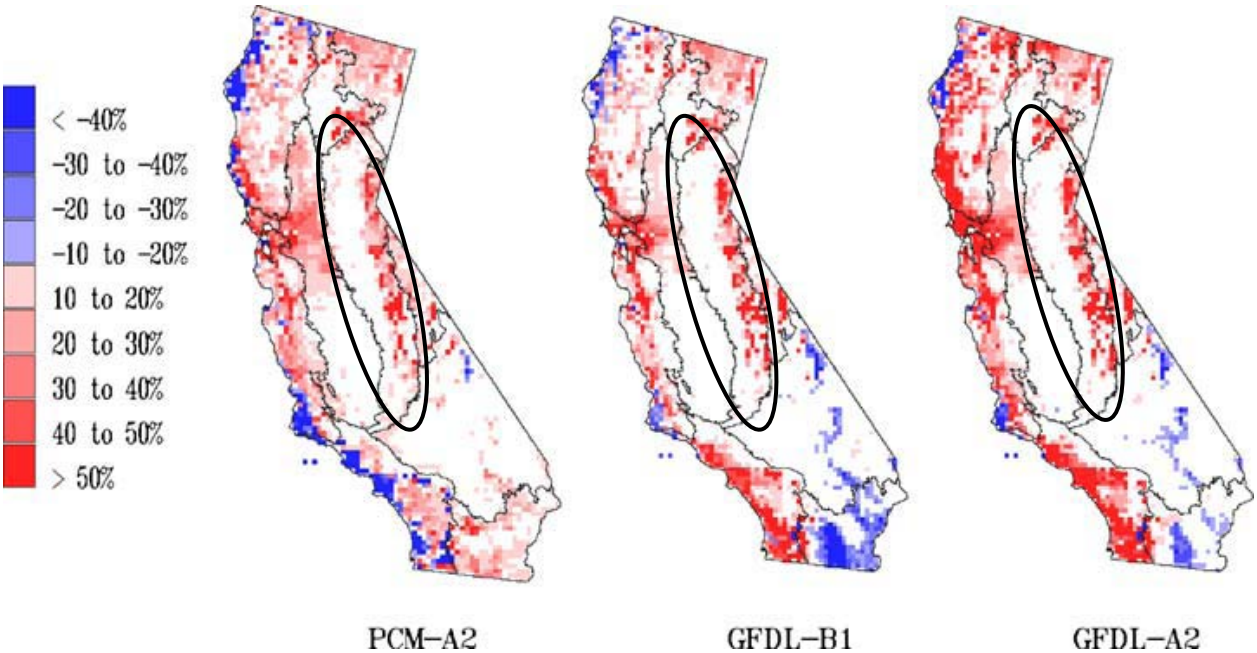

Figure 13. Percent change in projected mean annual area burned for the 2050-2099 period relative to the mean annual area burned for the historical period (1895-2003). Sierra Nevada is circled. Figure from Lenihan et al. (2008). See Fig. 11 for description of the climate and emissions scenarios (PCM-A2, GFDL-B1, GFDL-A2).

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