A summary of current trends and probable future trends in climate and climate-driven processes in the Inyo National Forest and adjacent lands.

Chris Mallek, Information Center for the Environment, University of California-Davis
crmallek@ucdavis.edu; 530-752-2644

Hugh Safford*, Regional Ecologist, USDA Forest Service, Pacific Southwest Region.
hughsafford@fs.fed.us; 707-562-8934

I. Local trends in climate over the past century

Several types of data are presented to illustrate climatic patterns within the Inyo National Forest and adjacent lands, hereafter referred to collectively as the "INF". First, spatially explicit weather records are presented as maps. These are derived using data from the PRISM climate dataset, which interpolates records from weather stations to all areas of the landscape for all years beginning in the late 19th century (Daly et al. 1994, PRISM 2010). Second, weather data are shown for the greater Mojave region (from the WRCC Climate Tracker website: http://www.wrcc.dri.edu/monitor/cal-mon/frames_version.html; Abatzoglou et al. 2009) as a whole, which includes the Inyo Mountains in the southeastern INF. This dataset is obtained by averaging PRISM data across the Mojave region for each year beginning in the late 19th century. Finally, data are also presented from three weather stations within the INF with long-term meteorological records. Records from these sites provide an indication of local-scale variation in climate patterns, and how patterns at individual stations differ in the extent to which they reflect those seen at broader, regional scales. Records from the Independence, Bishop, and Barcroft stations were used because they were the longest, most complete weather records obtainable within the INF. The former two stations are located in the Owens Valley, and bounded to west and east by the Sierra Nevada and White-Inyo Mountains of the Inyo National Forest. The station at Independence (36°48'N, 118°12'W) lies at 3,910' above sea level, and provides weather data from 1925 to 2008. The station at Bishop (37°22'N, 118°25'W) lies approximately 40 miles (64 km) north of the Independence station, at 4,150' above sea level, and provides weather data from 1949 to 2009. Years with more than 15 days of missing temperature data in a single month or 5 days of missing precipitation data in a single month (except between June and September) are excluded from the analyses. The Barcroft station (37°35'N, 118°25'W) is located in the White Mountains, about 17 miles (28 km) northwest of Bishop, at 12,444' above sea level, and provides daily minimum and maximum temperatures for most years between 1951 and 2009.

Temperature
The spatially explicit PRISM dataset indicates that mean temperatures in the INF during the 2000s were generally greater than they were during the 1930s (Fig. 1). This is consistent with the positive trends seen for the greater Mojave region when PRISM temperature values are averaged across the region and plotted by year for 1895-2009 (Table 1, Fig. 2A). Nevertheless, records from individual stations show that local patterns may vary considerably from site to site. At Independence, annual mean temperatures, mean maximum (i.e., daytime) temperature, and mean minimum (i.e., nighttime) temperatures have each risen by more than 3° F between 1925 and 2008 (Table 1, Fig. 2B). Between 1951 and 2009, mean maximum and mean minimum

*Corresponding author

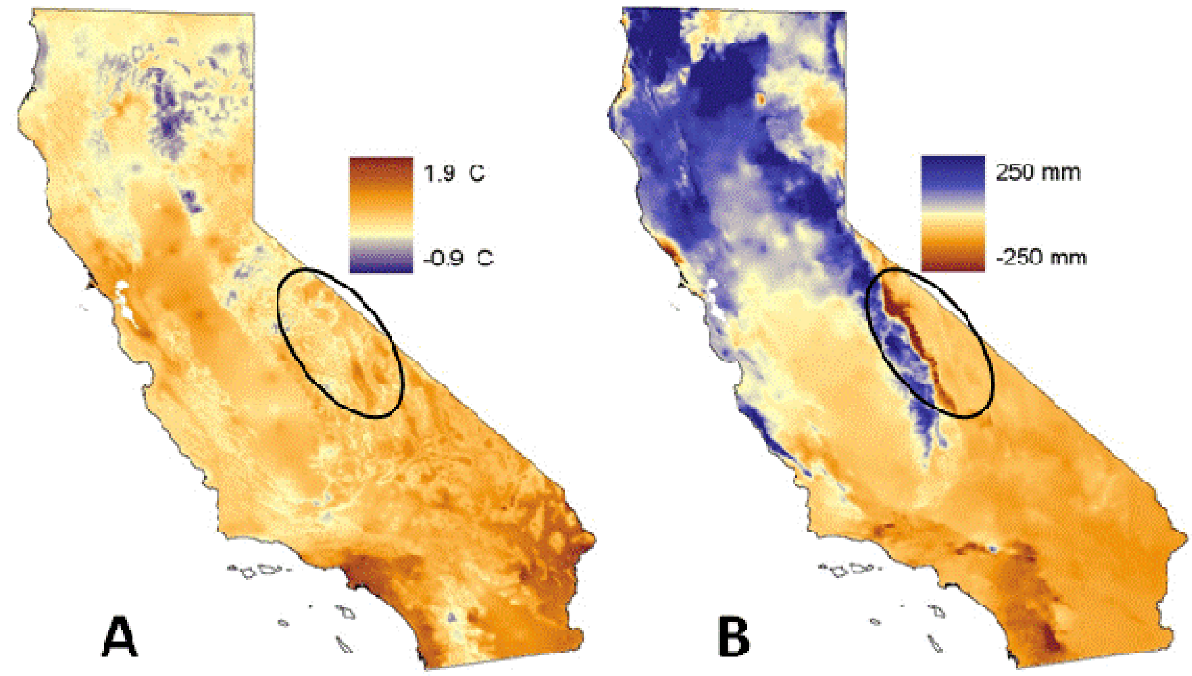

Figure 1. Spatial differences in mean annual temperature (A), and mean annual precipitation (B) between the 1930's and 2000's, as derived by the PRISM climate model. The INF area is found within the circle. Temperatures have risen across most of the INF area, but precipitation trends are variable across the area. Graphic courtesy of S. Dobrowksi, Univ. of Montana.

temperatures also increased at the Barcroft station (Table 1, data not shown). However, the 61-year record from Bishop (1949-2009) shows no statistically significant trends.

Precipitation

The three datasets used here fail to conclusively show any directional change in annual precipitation in the INF over the last ¾ century. The spatially explicit PRISM dataset for the INF shows that annual precipitation trends are variable across the INF landscape. The model suggests that precipitation has increased along the eastern slope of the southern Sierra Nevada, strongly decreased in the Long and Owens Valleys, and decreased moderately in the White and Inyo Mountains (Fig. 1). When PRISM data for mean annual precipitation are averaged across the greater Mojave region (which includes the Inyo Mountains) and plotted by year, they suggest a gradual increase in mean annual precipitation for this part of the INF area (Table 1, Fig. 3A). Records from Independence (1925-2008; Table 1, Fig. 3B) and Bishop (1949-2009; Table 1, Fig. 3C), which are in the Owens Valley, fail to show any statistically significant shift in precipitation totals, regardless of whether totals are calculated by calendar year (January – December) or by water year (July – June).

Precipitation in the greater Mojave (1895-2009), at Independence (1925-2008) and at Bishop (1949-2009) varied greatly among years during the periods of record, yet when precipitation totals were calculated by calendar-year, the magnitude of interannual variation increased at only one of three sites (Table 1, Fig. 3). However, when precipitation totals were calculated by water-

Table 1. Direction, magnitude, and statistical significance of climatic shifts at Independence, Bishop, and for the greater Mojave region. 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. For example, a positive value indicates an increase in the expected value of a climatic variable over time. 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. Results shown in parentheses are those obtained from data organized by water-year, otherwise data organized by calendar-year.

	Greater Mojave 1895-2009	**Independence 1925-2008**	**Bishop 1949-2009**	**Barcroft 1951-2009[1]**
Temperature				
Mean (°F)	+2.1***	+3.2***	ns	-
Max. (°F)	+1.9***	+3.5***	ns	+1.6***
Min. (°F)	+2.3***	+3.1***	ns	+2.7***
Precipitation				
Total (in.)	+1.8* (+1.8*)	ns (ns)	ns (ns)	-
Coefficient of variation	+17.6*** (+22.5***)	ns (+18.8*)	ns (ns)	-
Snowfall (in.)	-	(-9.2**[2])	(ns[3])	-

[1] = missing years 1980–1999, [2] = 1929/1930-2006/2007, [3] = 1949/50-1994/1995

year, interannual variation in total precipitation was found to have increased significantly at two of the three stations (not at Bishop). We note that while analyses based on calendar-year data may be useful for making comparisons with trends from other regions, interannual variation in water-year precipitation is likely of greater interest in the INF 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.

Annual snowfall at Independence declined by approximately 9.2 in. between 1929/1939-2006/2007, possibly as a result of increasing temperatures during the same period. In contrast, annual snowfall at Bishop changed little overall. Mote et al. (2005) reported increases in early-spring (April 1) snowpack and snow-water equivalents between 1950 and 1997 for most of the stations they surveyed in the southern Sierra Nevada (Fig. 4). This makes sense when viewed alongside the spatially explicit PRISM data (Fig. 1). The southern Sierra Nevada is so high that most precipitation continues to fall as snow despite the observed increases in temperature. Thus, increases in precipitation lead to greater snowpack which persists for a longer period of time into spring.

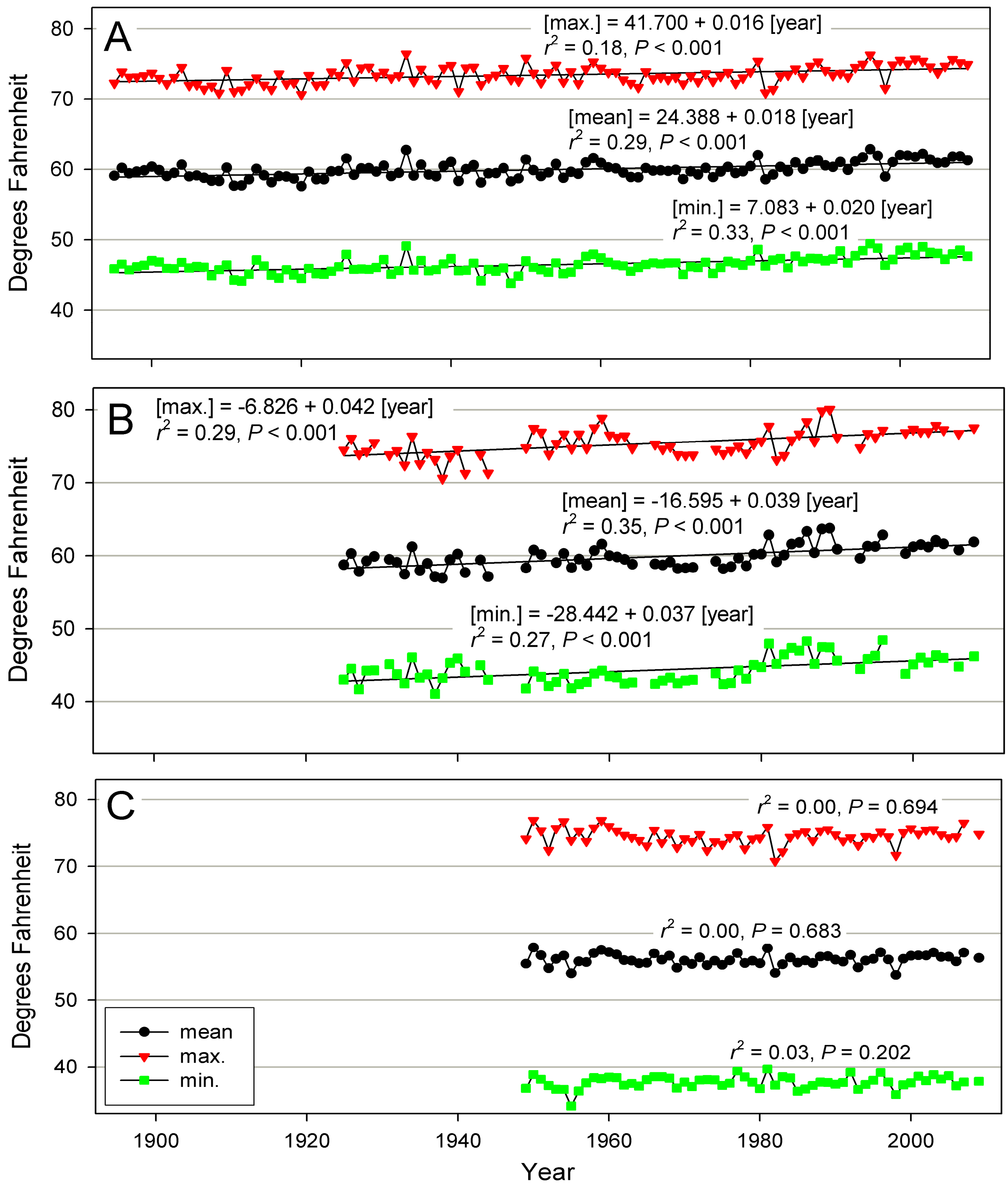

Figure 2. Annual mean, mean maximum, and mean minimum temperatures plotted by year for (A) the greater Mojave region, CA, 1895-2009; (B) Independence, CA, 1925-2008; and (C) Bishop, CA, 1949-2009. Coefficients of determination and statistical significance are shown for the relationships between each temperature variable and time. Lines of best fit and linear regression equations shown for significant regressions. No transformations were employed. Data from WRCC 2010.

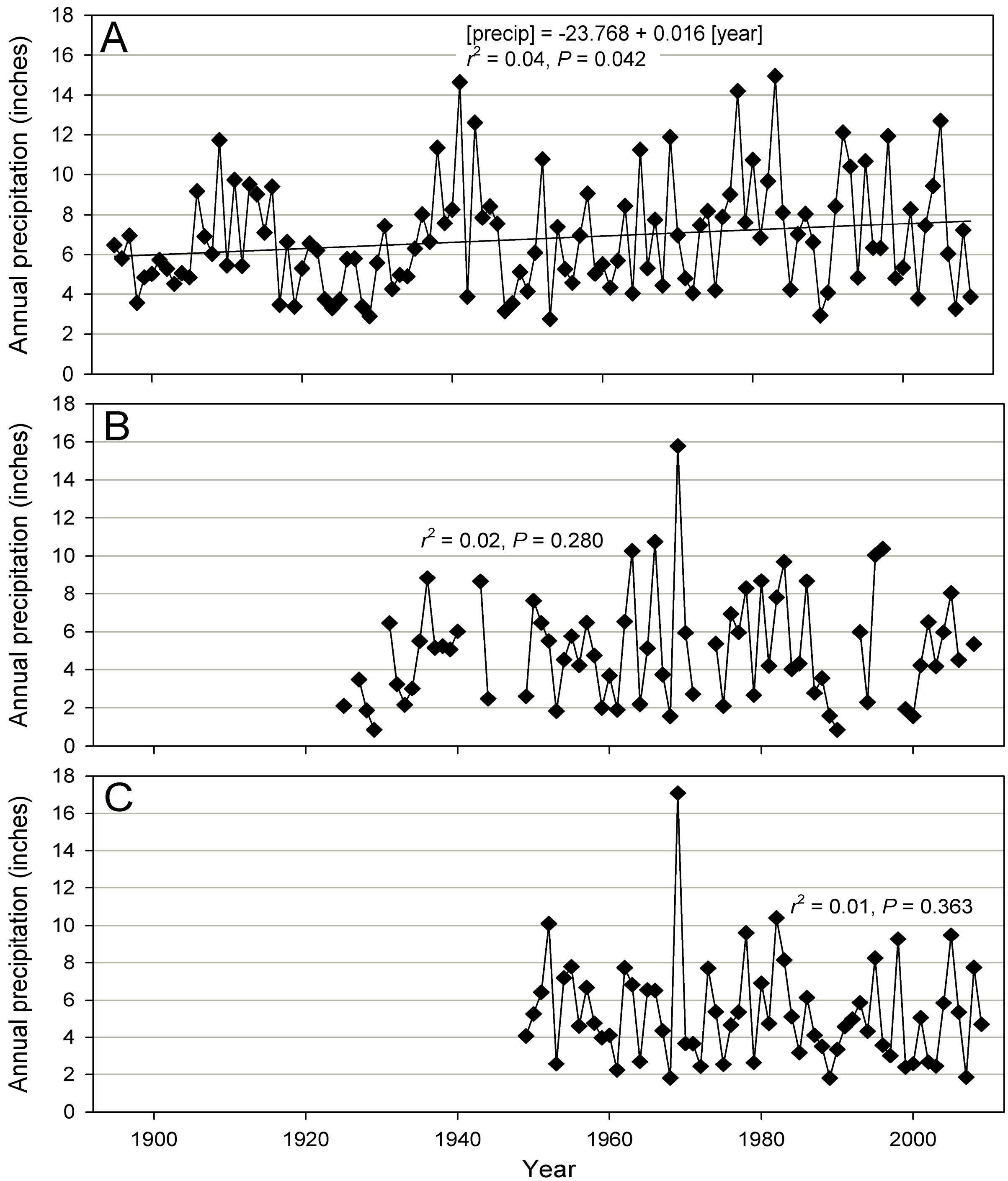

Figure 3. Annual (calendar-year) precipitation plotted by year for (A) the greater Mojave region, CA, 1895-2009; (B) Independence, CA, 1925-2008; and (C) Bishop, CA, 1949-2009. Coefficients of determination and statistical significance are shown for the relationships between annual precipitation and time. Lines of best fit and their equations are only shown for linear relationships with slopes significantly different (P < 0.05) from zero. No transformations were employed. Data from WRCC 2010.

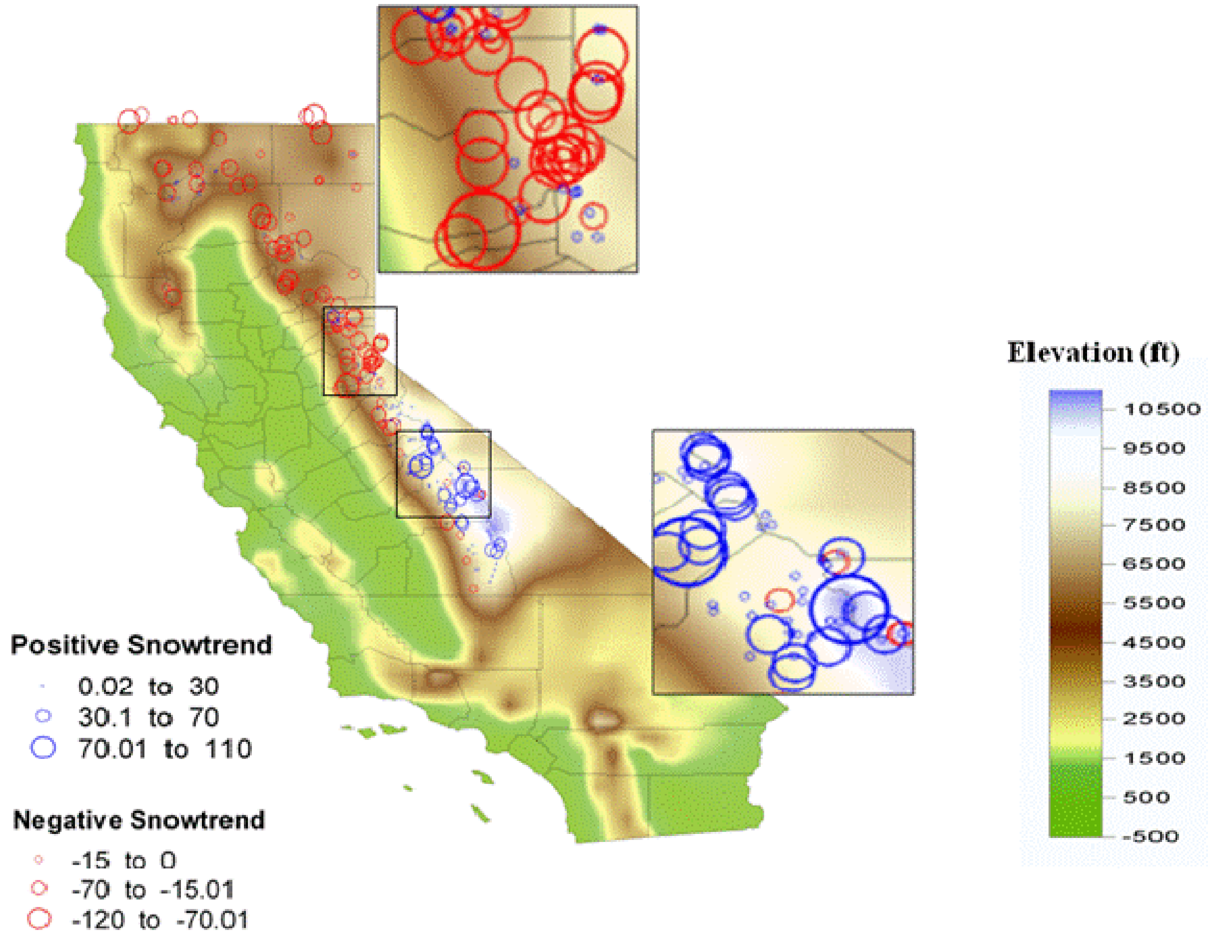

Figure 4. Trends in the amount of water contained in the snowpack ("snow water equivalent") on April 1, for the period 1950-1997. Red circles indicate percent decrease in snow water, blue circles indicate increase in snow water. From Moser et al. (2009).

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

Hydrology

Although they were unable to obtain streamflow data for streams in the INF, 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 (measured as the center of mass annual flow) occurred 0-15 days earlier. However, very few of these trends were statistically significant. During the same period, March flows in the studied streams were significantly higher by 3-10%, whereas June flows were mostly lower by the same amount; overall spring and early summer streamflow was down in most studied streams. It may be that higher winter precipitation in the southern Sierra Nevada has simultaneously produced deeper early-spring snowpack at high elevations (Mote et al. 2005) and greater March runoff (Stewart et al. 2005). Meanwhile, increases in spring temperatures may have led to an intensification and compression of the snowmelt period such that June flows have gradually declined (Stewart et al. 2005).

Kattelmann (2000) examined records of annual peak flows dating back to the 1920s for Convict, Rock, Pine, Big Pine, and Independence Creeks, all of which lie within the INF. These data revealed a disproportionately high degree of interannual variability during the most recent years. In the 75-year record (1926-2000), seven of the largest (by volume) eight to eleven (depending on which stream being considered) peak flows had occurred within the most recent 23 years. Six of the thirteen or fourteen smallest peak flows had occurred within the most recent 14 years. While this fails to present a clear trend, these patterns may indicate greater variation in the intensity of the peak snowmelt period, possibly due to variation in winter snowpack development, spring temperatures, or both.

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 as 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) included the INF in a study examining changes in mean fire size, maximum fire size, and total burned area across the Sierra Nevada as a whole. They showed that all three indices had 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 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.

There are some reasons to suspect that fire activity in the INF may not yet be changing as dramatically as in the remainder of the Sierra Nevada. Many ponderosa pine and mixed-conifer forests on the western slopes of the range, as well as other eastside Jeffrey pine forests north of the INF, experienced a strong decline in fire activity in the late nineteenth century due to increased human activity. However, North et al. (2009) examined fire history in Jeffrey pine forests throughout the INF and found evidence that fire activity had continued at most sites, albeit at reduced levels in some cases, into the 1950s. Notable exceptions include areas near human residences such as Whitney Portal (North et al. 2009) and Mammoth Lakes (Stephens 2001). Nevertheless, because it seems Jeffrey pine forests of the INF have largely not yet developed the extreme fuel conditions commonly found in other Sierra Nevada pine forests (Stephens 2001, North et al. 2009), fire activity in these forests may not yet be responding to changes in climate as dramatically as broader analyses (above) suggest.

Forest structure

Fire suppression has been practiced as a federal policy since 1935. Compared to low and middle elevation forests of the Sierra Nevada, pre-Euroamerican fire intervals in high elevation forests such as red fir (>50 years in most places) and subalpine forests (>100 years) were long enough that fire suppression policy has had little or no impact on ecological patterns or processes (Miller et al. 2009, North 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. Thus, changes over the last century in forests at high elevations are more likely to be driven by climate than by any direct human influence. This is further supported by studies showing that subalpine tree growth, stand structure, and treeline location have been strongly correlated with changes in precipitation and temperature in the long-term past (Graumlich 1991, Lloyd 1997, Lloyd and Graumlich 1997, Millar et al. 2007, Salzer et al. 2009).

Studies performed mainly in western Sierra Nevada subalpine forests provide an indication of probable trends within similar forests on the east side of the range. In the early 1930's, the Forest Service mapped vegetation in the Lake Tahoe Basin and neighboring National Forests, 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 from Yosemite National Park to the Plumas National Forest. These changes varied depending on tree species, age class, and forest type. 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 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 appeared to be responding favorably to increased warming and/or increased precipitation throughout the subalpine forest. Dolanc et al. (in review) attempted to re-locate and resample Wieslander plots in the subalpine zone between Yosemite National Park and the Lake Tahoe Basin. 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.

Bouldin (1999) and Dolanc et al. (in review) also studied patterns of tree mortality. In his 1935-1992 dataset, Bouldin (1999) 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) is actually making conditions better for some tree species in this stressful environment. Dolanc et al.'s (in review) direct plot-to-plot comparison 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.

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). Likewise, van Mantgem et al. (2009) ascribed the mortality patterns they analyzed to regional climate warming and associated drought stress. Higher elevation forests (>6700 feet) showed the lowest mortality rates, corroborating the Bouldin (1999) findings.

One example of recent climate-induced mortality in higher-elevation forests comes from the northern portion of the INF. Here, Millar et al. (2007) examined patterns of tree growth and mortality in limber pine forests at the lower end of the species' local elevation range (8038-9777 feet). Researchers found that limber pine growth responded negatively to drought, and that as temperature rose during the 20th century, trees became increasingly sensitive to periods of low precipitation. This resulted in pulses of mortality within the densest stands in the INF. Interestingly, these reductions in stand density seem to have reduced competition among neighboring trees to the point where subsequent droughts have had little effect on mortality levels.

Comparisons of the 1930's Wieslander vegetation inventories and maps with modern vegetation maps and inventories show large changes in the distribution of many vegetation types in the Sierra Nevada over the last 70-80 years (Fig. 5A, 5B; 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 (Fig. 6). 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 nearly century-long changes in Yosemite's vertebrate fauna across this elevation gradient, stretching across numerous vegetation types (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

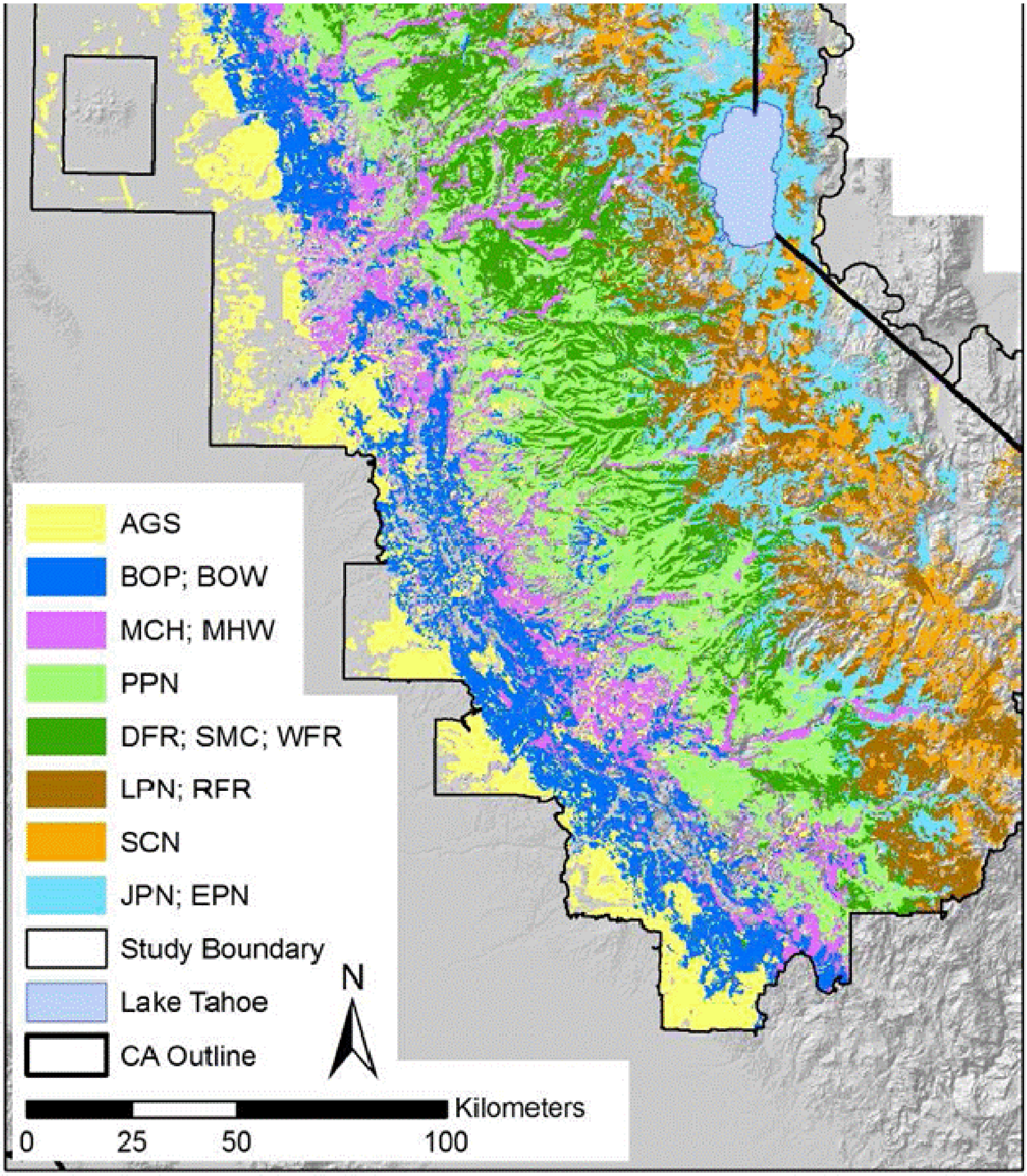

Figure 5. (A) Distribution of major vegetation types in the central and northern Sierra Nevada in the period 1932-1936. Mapped by the US Forest Service "Wieslander" mapping project. Maps digitized and vegetation types cross-walked to CWHR type by UC-Davis Information Center for the Environment. The INF region is just off the map to the southeast (lower right). 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.

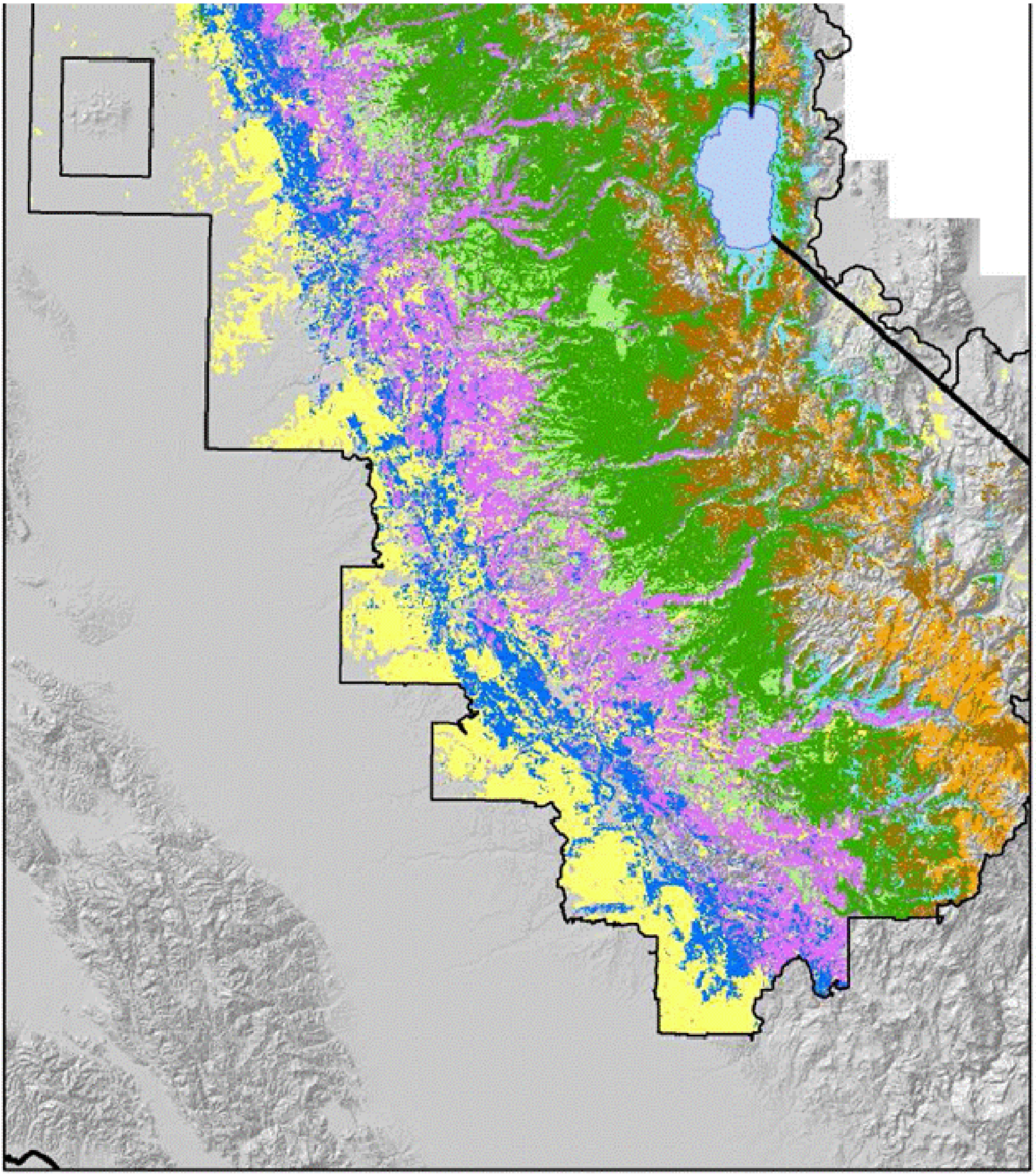

Figure 5. (B) Distribution of major vegetation types in the central and northern Sierra Nevada in 2000. Mapped by the US Forest Service Pacific Southwest Region Remote Sensing Laboratory. See Fig. 5 (A) for key and scale. The major patterns of change between 1934 and 2000 are: (1) loss of yellow pine (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. The INF region is just off the map to the southeast (lower right).

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 and secondarily to climate change.

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 INF. 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. (2004). Hayhoe et al. (2004) 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 degrees F in the winter, and 4-8 degrees in the summer. Finally, three of the four GCM × emissions scenarios employed by Hayhoe et al. (2004) predicted strong decreases in annual precipitation by 2100, ranging from -91 to -157%; the remaining scenario predicted a 38% increase.

Coats et al. (2010) recently downscaled the GFDL and PCM General Circulation Models (GCMs) from the original 100 x 100 km output grid to a 12 x 12 km grid and provided 21st century projections of future climate and hydrology trends for the Lake Tahoe Basin, to the north of the INF area but in a similar geographic situation to the northern part of the INF. Coats et al. used the IPCC A2 (strong increase in Greenhouse gases [GHGs]) and B1 (moderate increase in GHGs) emissions scenarios. Coats et al.'s (2010) results project strong upward trends in maximum and minimum temperatures, with an increase of up to 9°F by 2100 under the A2 emissions scenario (the equivalent of dropping the elevation of the Tahoe Basin by over 2500 feet), but no strong trends in annual precipitation amount, except for a slight drying trend projected by the GFDL-A2 scenario toward the end of the century. Coats et al. (2010) also project a continuing shift from snowfall to rain (from about 35% snowfall currently to 10-18% by 2100).

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. [2004] 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 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. 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.

In their recent assessment of potential climate change and hydrology trends in the Lake Tahoe Basin, Coats et al. (2010) project a continuing trend toward earlier snowmelt and runoff during the water year; increases in drought severity, especially toward the end of the century; and dramatic increases in flood magnitude in the middle third of the century, especially under the B1 emissions scenario. Current snowpack duration in the LTB is between 240 and 250 days. Under the most extreme future climate x emissions scenario (GFDL-A2), Coats et al. (2010) project a mean snowpack duration of only 184 days by the last third of the 21st century. The same scenario projects a loss in stream inflow into Lake Tahoe of 20-40% of baseline (average of 1967-1999) by 2100. As noted above, these trends are probably at least grossly applicable to the northernmost portion of the Inyo NF.

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 INF 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. Under their three future scenarios, Lenihan et al. (2003, 2008) projected for the INF area a general decline in the extent of most conifer-dominated vegetation types, including evergreen conifer (montane) forest and subalpine forest (Fig. 6). Forest types including broadleaved species (mostly oaks, but potentially also aspen) are projected to expand, especially where water balance is sufficiently high (i.e. in the Sierra Nevada). Shrublands and pinyon-juniper woodlands are projected to transition in many cases to grass-dominated systems, as fire frequency increases with warming temperatures, drier summers, and increased ignitions (Fig. 6; Lenihan et al. 2008). Hayhoe et al. (2004) 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 (Fig. 7). 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

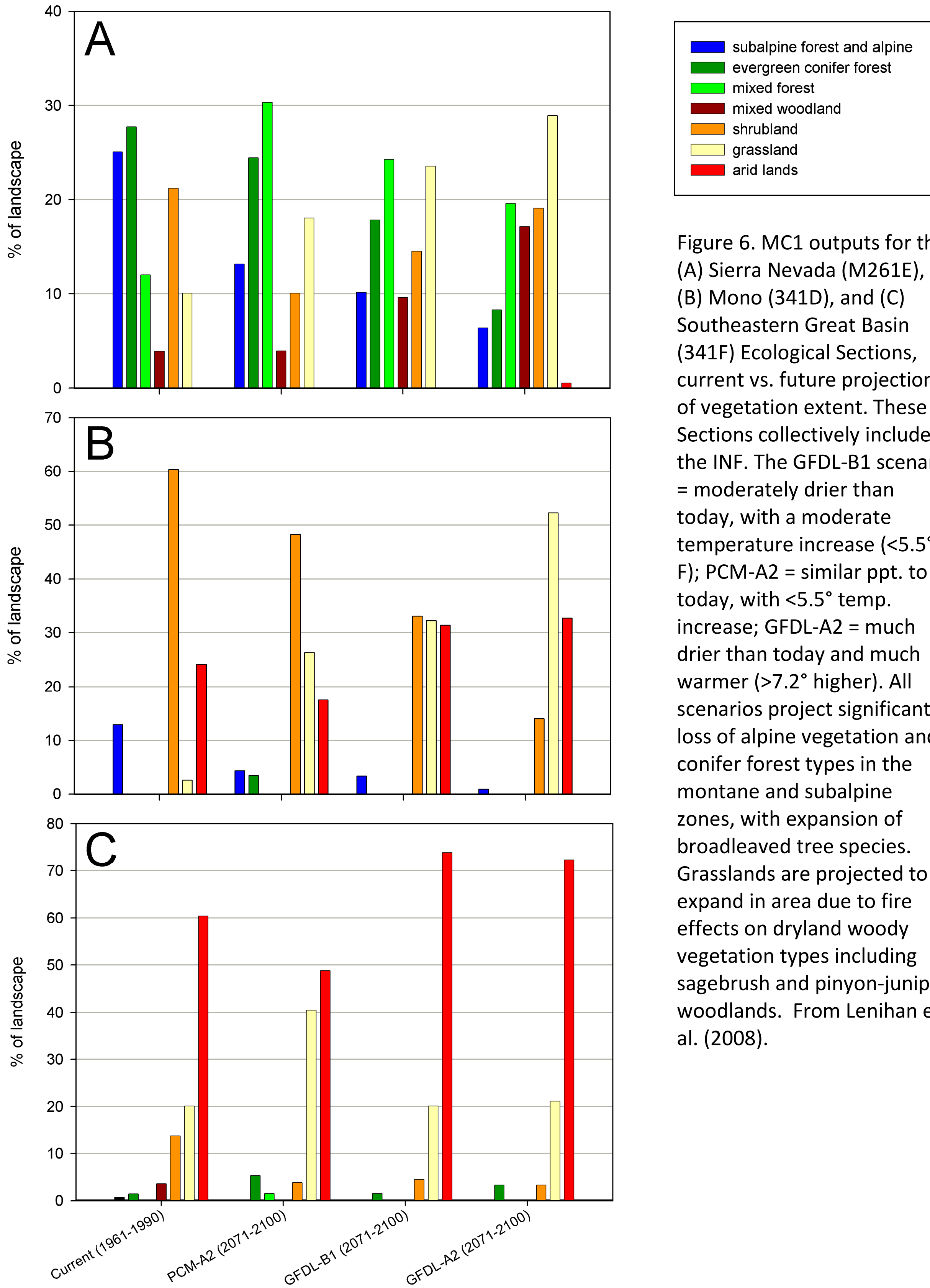

Figure 6. MC1 outputs for the (A) Sierra Nevada (M261E), (B) Mono (341D), and (C) Southeastern Great Basin (341F) Ecological Sections, current vs. future projections of vegetation extent. These Sections collectively include the INF. The GFDL-B1 scenario = moderately drier than today, with a moderate 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 alpine vegetation and conifer forest types in the montane and subalpine zones, with expansion of broadleaved tree species. Grasslands are projected to expand in area due to fire effects on dryland woody vegetation types including sagebrush and pinyon-juniper woodlands. From Lenihan et al. (2008).

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). 70 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. As suggested above, several studies suggest that forest fuel conditions in the INF might not yet be as extreme as those found in other forest types across the state, due to a shorter history of effective fire suppression (Stephens 2001, North et al. 2009) and lower site productivity.

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. 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. 2004), 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

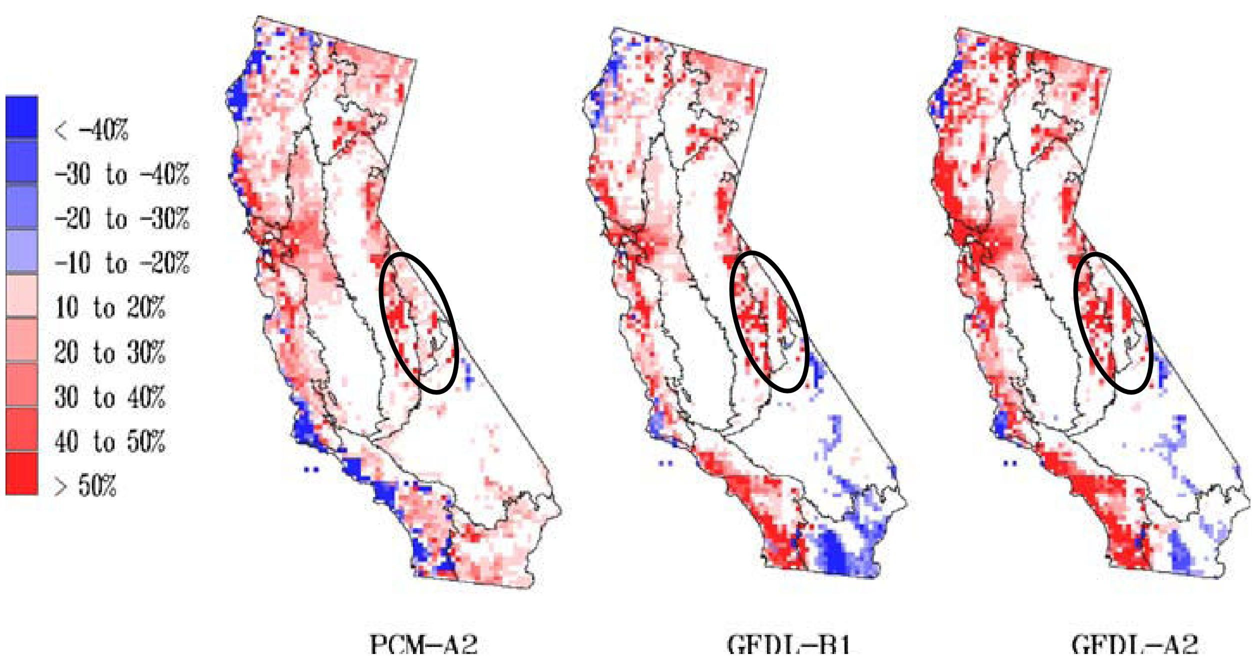

Figure 7. Percent change in projected mean annual area burned for the 2050-2099 period relative to the mean annual area burned for the historical period (1895-2003). INF area is circled. Figure from Lenihan et al. (2008). See Fig. 6 caption for description of the climate and emissions scenarios (PCM-A2, GFDL-B1, GFDL-A2).

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.

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