A summary of current trends and probable future trends in climate and climate-driven processes for the Angeles and San Bernardino National Forests

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I. Introduction

This summary of climate and climate-driven trends in southern California is a product of the Forest Service's Pacific Southwest Region Ecology Program. This document synthesizes and summarizes current trends and projected future trends related to climate change on the Angeles and San Bernardino National Forests and surrounding lands in southern California. This analysis is primarily based on local weather station data, PRISM data, and published literature; in some instances, important and credible findings from unpublished studies are also included. The summary begins with local and regional trends in temperature and precipitation, then examines how these trends are affecting hydrology, fire, vegetation and wildlife in the study area. A summary of projected future trends in climate and climate-affected resources is also provided. This document provides information of fundamental importance for National Forest management and planning in the face of global change. This summary is a living document and will be updated regularly.

II. Local and regional trends over the last century linked to climate change

The temperature and precipitation data presented in this section are derived from seven weather stations in the vicinity of the Angeles and San Bernardino National Forests (ANF and BDF) (WRCC 2013). We evaluated weather records for trends in annual mean temperature, annual mean minimum temperature, annual mean maximum temperature, total annual precipitation, interannual variability in precipitation, and total annual snowfall. Weather stations were selected for inclusion based on their location relative to the ANF/BDF Forests and the length and completeness of their records. For details on weather stations selected and station data analysis, see appendix A. Also, spatial data from the PRISM climate dataset are presented, which extrapolates weather station data records to the landscape for years beginning in the late 19th century (Daly et al. 1994, PRISM 2010).

Temperature and Precipitation

Temperature

Southern California has shown the greatest warming trends in California over the last century, with accelerated warming in the last 35 years (Cordero et al. 2011). The PRISM data suggest that the ANF/BDF area has experienced temperature increases of about 1.8° to 3.6°F (1° to 2°C) over the last ¾ century (Fig. 1). This pattern is consistent with the temperature data from the seven weather stations. All stations show statistically significant increases in at least one of the temperature parameters (mean minimum, mean annual, and mean maximum; Table 1, Fig. 2). For five of the seven stations, increases were greatest in mean minimum (nighttime) temperatures (Table 1; Fig. 2). The two stations with the largest increases in mean minimum temperature are located in urban settings, consistent with findings of LaDochy et al. (2007), who noted strong local effects of urban heat generation and retention (by concrete and asphalt, e.g.) on warming in the Los Angeles Basin.

The occurrence of nighttime freezing temperatures is significantly decreasing at three of the stations (Table 1, Fig.3). For example, at the beginning of the Idyllwild data record five to six months per year could be expected to have average nighttime temperatures that fall below freezing. Today the average is three to four months, and the trend is strongly downward. The trend is similar for Mt. Wilson No. 2 and Palmdale.

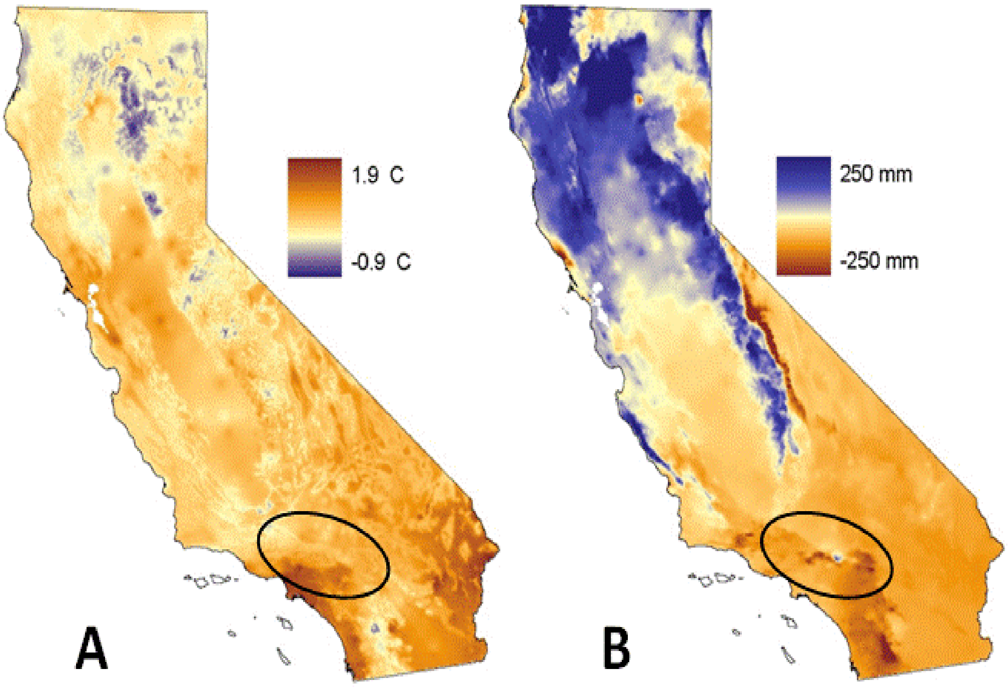
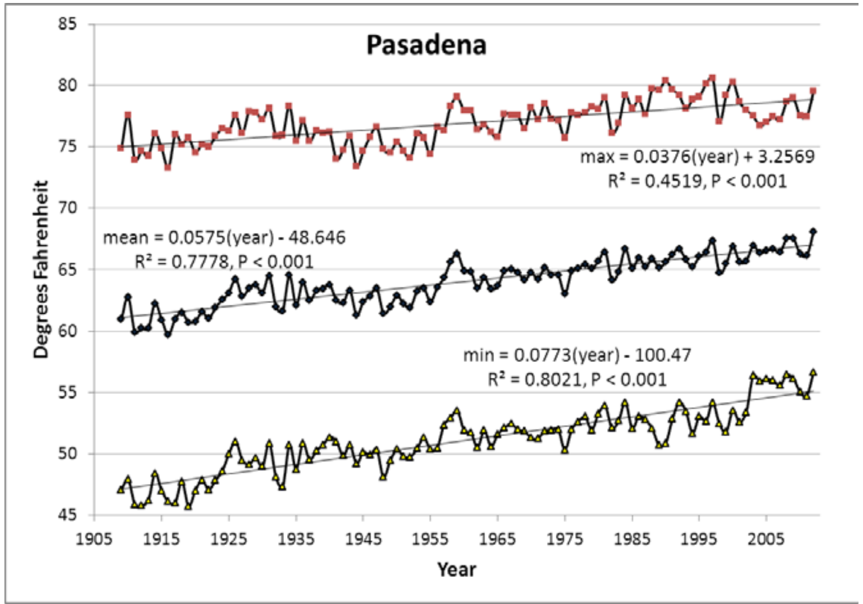
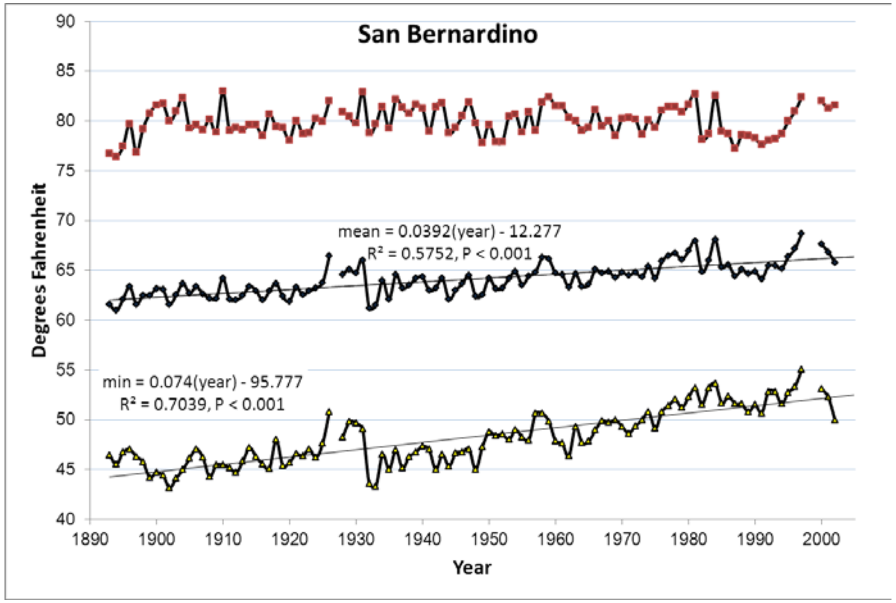


Figure 1. Spatial representations of differences in mean annual temperature (A), and mean annual precipitation (B) between the 1930's and 2000's, as derived by the PRISM climate model. The Angeles and San Bernardino National Forests area is found within the circle. According to PRISM, temperatures have risen and precipitation decreased across most of the area. Graphic courtesy of S.Dobrowski, Univ. of Montana.

Table 1. Direction, magnitude and statistical significance of climatic shifts at seven weather stations in the area of the Angeles and San Bernardino National Forests. Numerical values indicate the difference between the expected values for the earliest and most recent years of the given time frame, as calculated from linear regression equations. Direction and magnitude of shifts are only shown for cases where rates of change are statistically greater or less than zero (P < 0.05). Statically 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

	Pasadena	**San Bernardino**	**Fairmont**	**Palmdale**	**Idyllwild**	**Mt Wilson No. 2**	**Lake Arrowhead**
Elevation	**860 ft**	**1170 ft**	**3060 ft**	**2660 ft**	**5380 ft**	**5710 ft**	**5200 ft**
Temperature							
Mean (°F)	+6.0***	+4.3***	+1.4**	+3.1***	+2.6***	+4.3***	ns
Max. (°F)	+3.9***	ns	+2.8***	+2.6***	ns	+5.2***	ns (-1.3, P=.052)
Min. (°F)	+8.0***	+8.1***	ns	+3.4***	+5.3***	+2.8***	+1.5**
Freezing (mo/yr)	ns	ns	ns	-1.0**	-1.8***	-1.2***	ns (-1.0, P=.061)
Precipitation							
Total (in.)	ns	ns	ns	ns	ns	Ns	ns
Coefficient of variation	+0.2***	ns	+0.4***	+0.4***	ns	Ns	ns
Snowfall (in)	ns	ns	-7.5*	-2.9*	-21.2*	Incomplete data	Incomplete data





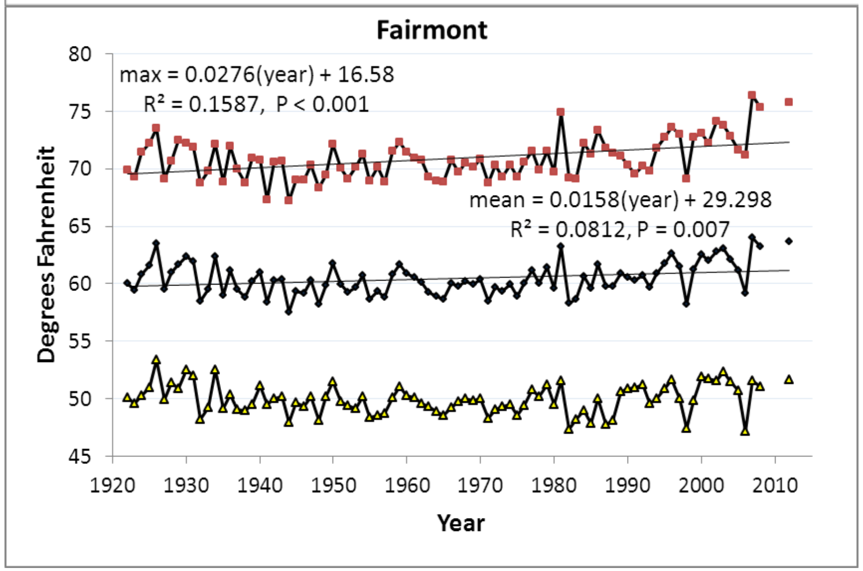
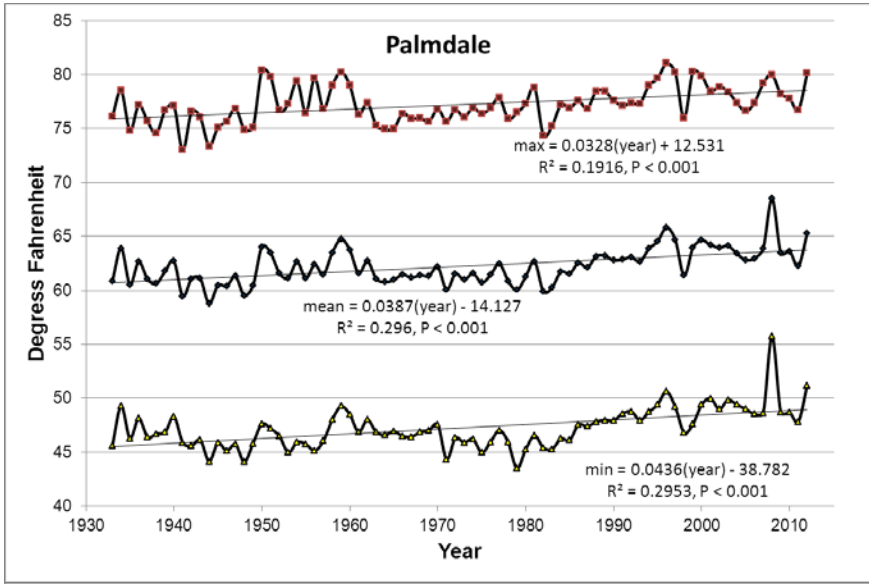
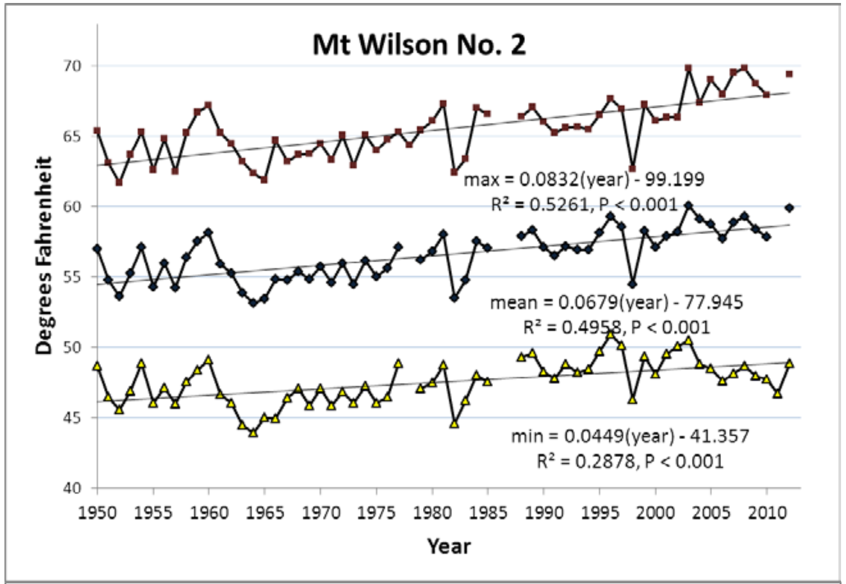
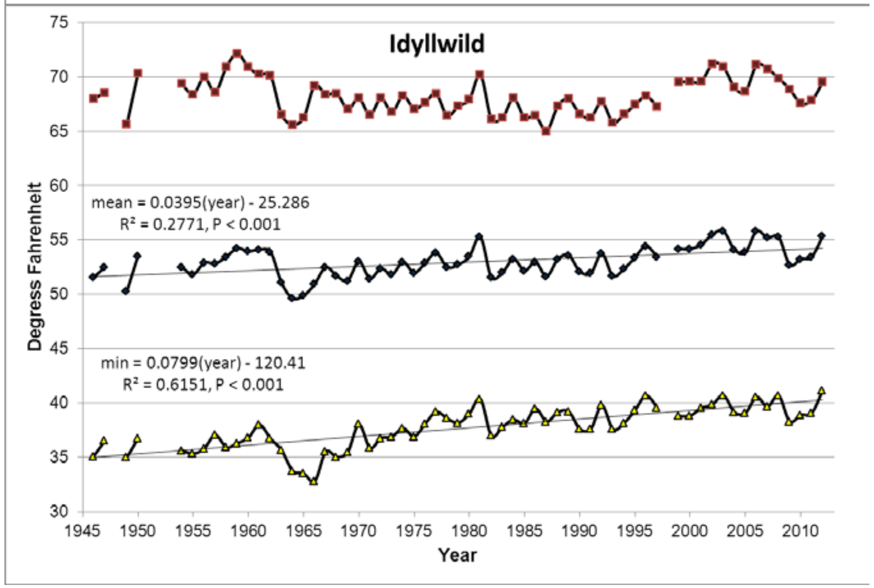


Figure 2. Annual mean, mean maximum, and mean minimum temperatures at seven weather stations. Linear regression equations, coefficients of determinations, and statistical significance shown for significant regressions only. No transformations were employed. Data from WRCC 2013. Note positive slopes for at least one temperature variable at each of the seven weather stations, indicating warming temperatures.


Palmdale
Degress Fahrenheit
85
80
75
70
65
60
55
50
45
40
1930
1940
1950
1960
1970
1980
1990
2000
2010
Year
max = 0.0328(year) + 12.531
R² = 0.1916, P < 0.001
mean = 0.0387(year) - 14.127
R² = 0.296, P < 0.001
min = 0.0436(year) - 38.782
R² = 0.2953, P < 0.001


Mt Wilson No. 2
Degrees Fahrenheit
70
65
60
55
50
45
40
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Year
max = 0.0832(year) - 99.199
R² = 0.5261, P < 0.001
mean = 0.0679(year) - 77.945
R² = 0.4958, P < 0.001
min = 0.0449(year) - 41.357
R² = 0.2878, P < 0.001


Idyllwild
Degress Fahrenheit
75
70
65
60
55
50
45
40
35
30
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Year
mean = 0.0395(year) - 25.286
R² = 0.2771, P < 0.001
min = 0.0799(year) - 120.41
R² = 0.6151, P < 0.001

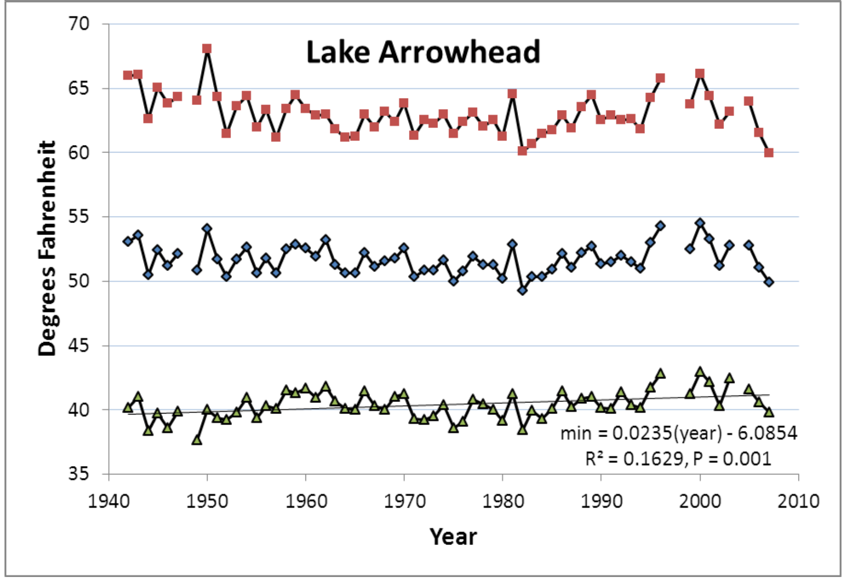
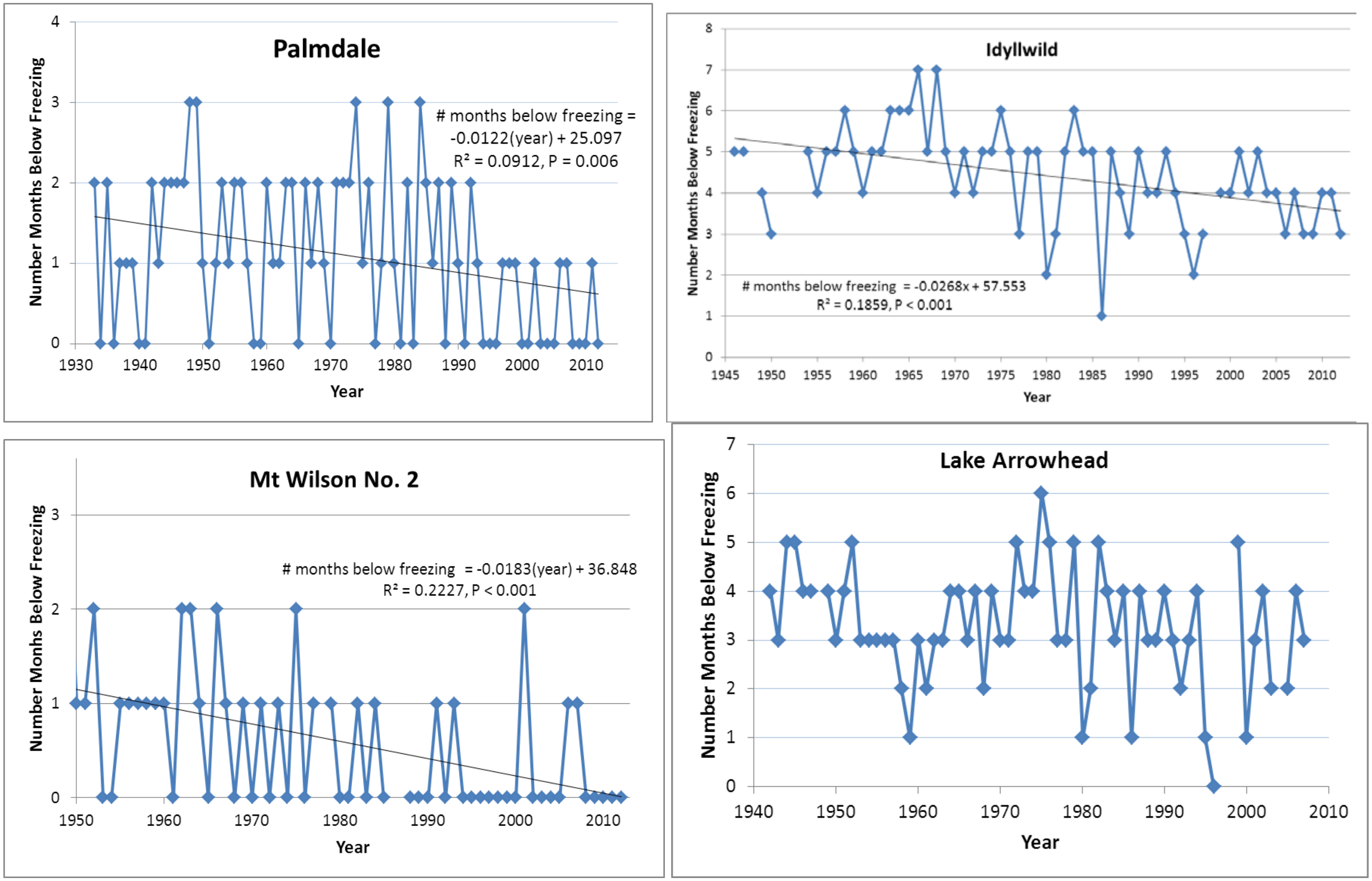

Lake Arrowhead
Degrees Fahrenheit
70
65
60
55
50
45
40
35
1940
1950
1960
1970
1980
1990
2000
2010
Year
min = 0.0235(year) - 6.0854
R² = 0.1629, P = 0.001

Figure 3. Number of months in which the average temperature remained below freezing for four weather stations. Linear regression equations, coefficients of determination and statistical significance shown for significant regressions only. No transformations were employed. Data from WRCC 2012.



Precipitation

The PRISM dataset suggests generalized drying across the ANF/BDF area (with the exception of the San Gabriel Mountains: Fig. 1), however there are no significant trends identified in the annual precipitation at the seven weather stations (Table 1; Fig. 4). Even with stable precipitation, the observed increases in temperature indicate an increase in evapotranspiration and thus drier ecosystem conditions overall. Monthly precipitation exhibited increases in interannual variability at three of the weather stations (Fig. 5). A 20-year study noted increased interseasonal variability in southern California precipitation between 1961 and 1980 (Kim et al. 2009). The Bureau of Reclamation performed basin level studies on the Santa Ana River Watershed on the San Bernardino National Forest, as well as for the local watersheds which feed into the Los Angeles Basin. Supporting the PRISM results, they found that overall precipitation, streamflow, and snowpack has declined across the Santa Ana River watersheds on the San Bernardino National Forest, as well as for the watersheds that feed into the Los Angeles Basin, with the exception of one location within the San Gabriel Mountains (initial findings presentation; website link).

At Pasadena, Fairmont and Palmdale, the 5 yr coefficient of variation for annual precipitation is rising strongly over time (Table 1, Fig.5), which demonstrates that year-to-year variability in precipitation has been increasing over the course of the last century at these stations. Southern California has the most variable rainfall regime of the world's Mediterranean climate zones, and has more intense summer drought compared to other Mediterranean sites, with only 5% of precipitation occurring in the summer time (Cowling et al. 2005). Additionally, precipitation occurs more infrequently in southern California than in other Mediterranean areas (Cowling et al. 2005). Even if mean annual precipitation is not changing, increases in interannual variability, which is already very high in southern California, have important implications for ecosystem, water, and fire management.

Givati and Rosenfeld (2004) suggest that urban air pollution (i.e., high levels of GHG and CO_2) from highly populated areas may also be contributing to rainfall suppression in California. Givati and Rosenfeld (2004) found that the western slopes downwind of Los Angeles and San Diego may have experienced a 15-25% suppression of orographic precipitation over the last century, while the drier eastern slopes have experienced a slight compensatory increase (Givati and Rosenfeld 2004).

While most of the weather stations do not receive snow, there are significant declining trends in annual snowfall amounts at three of the seven weather stations analyzed (Palmdale, Idyllwild and Fairmont) (Table 1, Fig.6). Lake Arrowhead also shows a very large decline in snowfall, but we chose to omit this station as the indicated declines are fairly incredible (loss of more than 80 inches per year) and there are many missing years of data.

Figure 4. Annual precipitation at four stations. No significant changes were observed. No transformations were employed. Data from WRCC 2013.

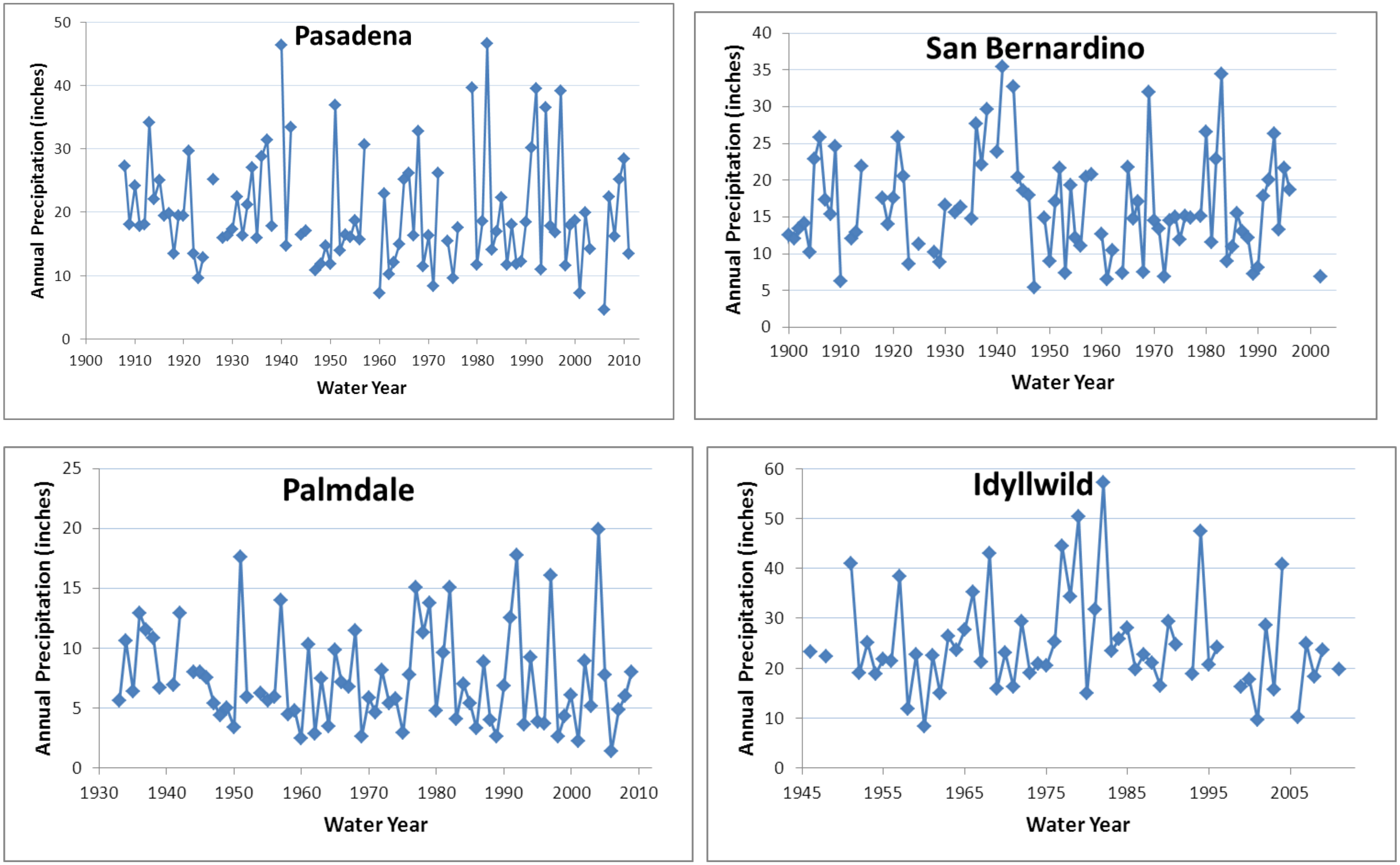
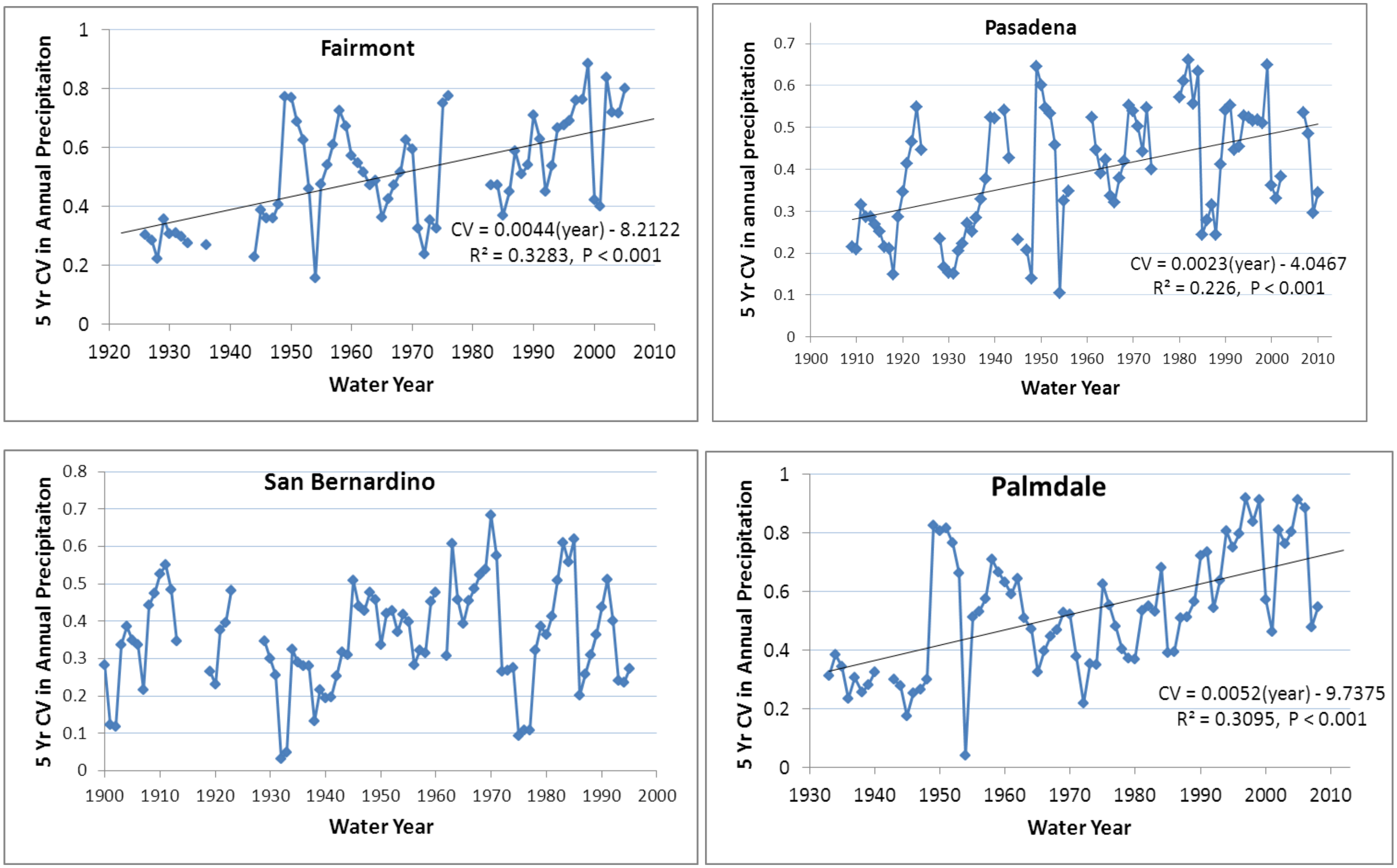


Figure 5. 5 year coefficients of variation in annual precipitation for four weather stations. Regression equations, coefficients of determination and statistical significance shown for significant regressions only, indicating an increase in variability of precipitation over time. No transformations were employed. Data from WRCC 2013.

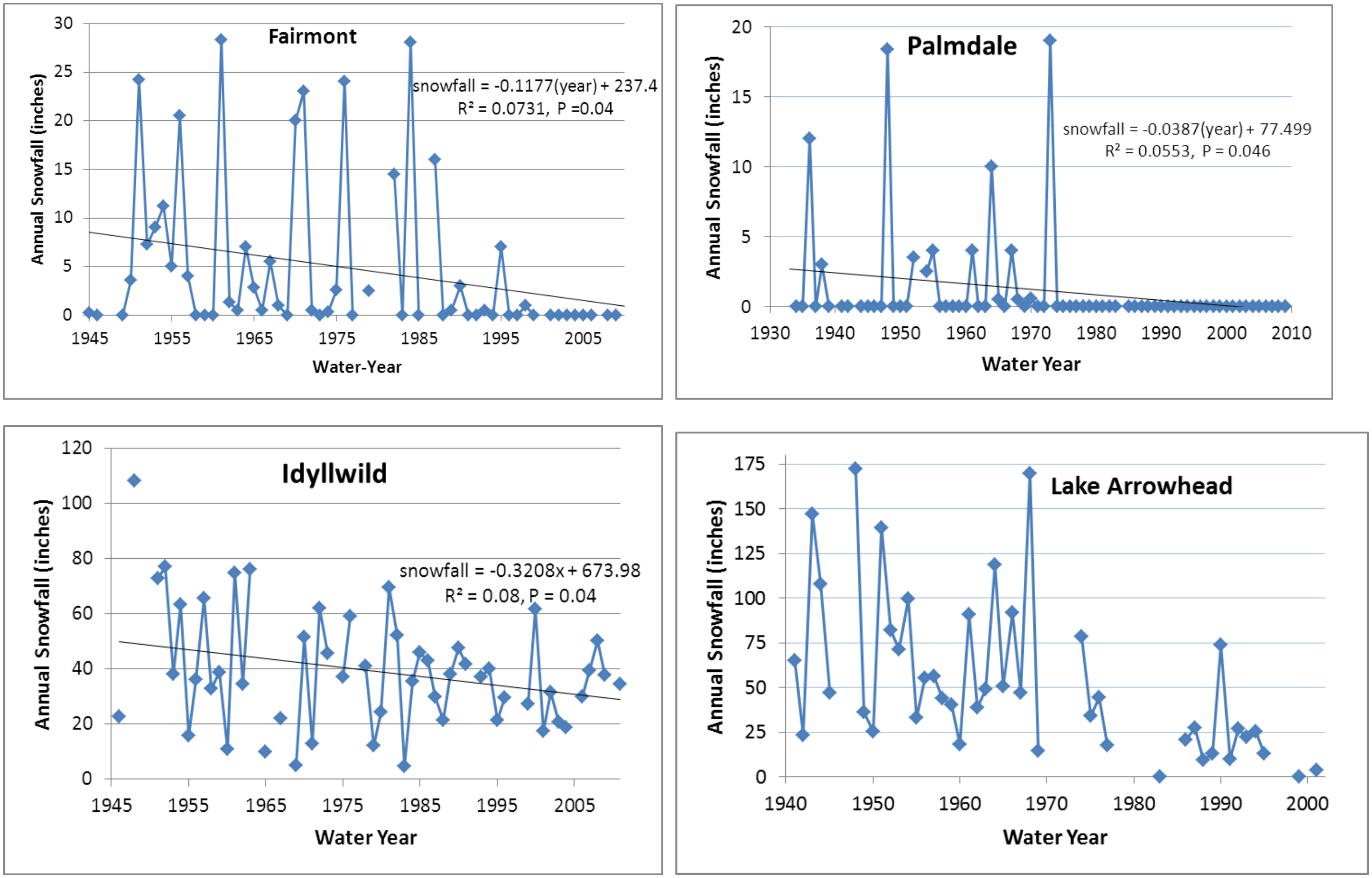


Hydrology

Across the western United States, widespread changes in surface hydrology have been observed since the mid-1900s. These shifts include: decreased snowpack (particularly at low elevation sites; Mote et al. 2005, Barnett et al. 2008, Grundstein and Mote 2010); earlier snow melt and spring runoff (by 0.3 to 1.7 days per decade; Stewart *et al*. 2005, Hamlet et al. 2007, Maurer 2007, Barnett et al. 2008); 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 and Garen 2005). Long term shifts in the timing of streamflow have been observed for snowmelt dominated basins since the late 1940's, resulting from early snow melt. (Mote 2003a, Hamlet et al. 2005, Mote et al. 2005, Regonda et al. 2005, Stewart et al. 2005). Moser et al. (2009) found that over the past 100 years, the fraction of annual runoff that occurs during April–July has decreased by 23% in the Sacramento River basin and by 19% in the San Joaquin River basin in California. During this same time snow pack accumulation has decreased (Mote et al. 2005). Knowles et al 2006 found that shifts in precipitation from rain to snow have occurred since the middle of the last century. There are also downward trends in April 1 snow water equivalent (SWE), especially in warmer coastal areas (Hamlet et al. 2005). In addition to temporal hydrological shifts, California has also exhibited one of the greatest increases in variability in streamflow in the western U.S. since the 1980s (Pagano and Garen 2005). Forest Service staff have noted that many seasonal and intermittent streams on Forest Service lands in southern California are drying earlier and exhibiting previously unseen dry stretches (M. Jennings, pers. comm.). This increased variability in high and low flows, coupled with high year-to-year persistence (i.e. the probability that a wet year is followed by another wet year or a dry year by a dry year), has resulted in extended and extreme dry and wet spells that are particularly challenging for management of urban infrastructure and other services (Pagano and Garen 2005).

Due to the combination of erosive, variable terrain and the position of the transverse mountain ranges in relationship to the coast, much of southern California is vulnerable to floods and debris flows after intense precipitation events, especially in areas with recent or recurrent fires (Gabet and Dunne 2003). Water and sediment flow in southern California has a history of dramatic fluctuations that have been largely driven by multidecadal climate variability and the El Nino/Southern Oscillation (ENSO) events (Inman and Jenkins 1999). For example, the sediment carried by the Santa Clara and Ventura Rivers during a single flood year (1969) was greater than the total transported by those rivers during the preceding 25-year period (Inman and Jenkins 1999). Additionally, rainfall was enhanced throughout southern California between 1950 to 1982 during the intensification of the subtropical westerly jet in response to ENSO (Schonher and Nicholson 1989). Highly episodic sediment flow, as seen in southern California, can lead to erosion, property damage, loss of life, and destruction of riparian habitats (Gabet and Dunne 2003). Combined with climate change effects of increased water temperatures, decreased dissolved oxygen levels, and increased toxicity of pollutants (Ficke et al. 2007), increases in turbidity or suspended solids due to erosion are likely negative effecting aquatic organisms.

Figure 6. Annual snowfall for four weather stations. Linear regression equations, coefficients of determination and statistical significance shown for significant regressions. No transformations were employed. Data from WRCC 2012. Lake Arrowhead not analyzed due to missing data.



Fire

Chaparral vegetation constitutes more than a third of the lands administered by the four southern California National Forests (Fried et al. 2004). The frequency of fires in low to mid elevation chaparral ecosystems has increased over the last few decades, due to increased human ignitions and increased climate variability (Pinol et al. 1998, Riera et al. 2007). Mean historic fire return interval in chaparral in lowland California was estimated by Van de Water and Safford (2011) to be about 55 years, ranging from 30-90 years (see also Barro and Conard 1991, Keeley and Fotheringham 2001, Lombardo et al. 2009). Presettlement fire intervals were probably longer in the Mojave area desert chaparral in southern California, whose shrub communities are typically less dense and more discontinuous (Brooks and Minnich 2006); Van de Water and Safford's (2011) literature summary estimates a 65 yr FRI for semidesert chaparral (range 50-115) before Euroamerican settlement. In southern California, many areas dominated by chaparral are burning more often now than they did before settlement (Safford and Van de Water 2013), and modern fire return intervals may now be 10-20 years or less (Safford 2007).

While historical fire size is debated, it appears that fire size and severity has also recently been growing in southern California. In bigcone Douglas-fir stands of the Los Padres National Forest, Lombardo et al. (2009) identified a shift to more severe fires after the late nineteenth century and also noted a shift to widespread, landscape-scale fires compared to previous mixtures of relatively large and small fires. Minnich (2001) suggested that suppression has created homogenous chaparral fuelbeds which have enabled the growth of unprecedented large-scale fires, but the evidence indicates that large fires were not historically atypical in chaparral fuels (Keeley and Zedler 2009), and fire suppression has had little effect on fire frequency in most of low- and middle-elevation southern California (Safford 2007). Others emphasize the role that drought and foehn (Santa Ana) wind events play in fire size (Keeley 2004, Moritz et al. 2004, Keeley and Zedler 2009), and attribute increases in the occurrence of large fires since 2000 to drought conditions, which increase dead fuel loading and hence spotting during wind-driven fire events (Keeley et al. 2009). The spread of non-native invasive herbaceous vegetation adjacent to the WUI exacerbates these issues, increasing fire risk due to the presence of readily-available fine fuels. Keeley (2004) found that area burned in chaparral fires in southern California was not closely related to antecedent climate variables, but rather to the occurrence of extreme weather at the time of burning. Syphard et al. (2007) found that human-related variables like population density and distance to communities were the best predictors of fire frequency in southern California. Exurban, or intermediate density development, as often seen in southern California National Forest WUI zones, is linked to the highest level of ignitions (Syphard et al. 2007). With its dense (637 people per mi^2) and growing (11% between 1990 and 2000) human population densities, southern California is at particular risk for increasing fire frequencies at lower elevation sites (Underwood et al. 2009).

The high frequency of fires at lower elevations in the southern California foothills is not seen in the southern California mountains, leading to different fire patterns at these higher elevation sites over the past century (Keeley et al. 2007). Mixed conifer forests in the Transverse and Peninsular ranges in southern California experienced frequent fires prior to the 20th century (Skinner et al. 2006), but contrary to low and mid elevation shrubland ecosystems, higher elevation coniferous forests of areas like the Upper San Gabriel, Upper San Gorgonio, and San Jacinto ecological subsections are now experiencing far fewer fires than was the case before Euroamerican settlement (Skinner et al. 2006, Safford and Van de Water 2013). While lightning-ignited fires once burned frequently in high elevation mixed conifer and yellow pine forests, fire suppression has succeeded in nearly eliminating wildfire as an ecological driver in these ecosystems (Safford 2007, Keeley et al. 2009). At many sites, evidence suggests a decline in fire frequency beginning around 1900 and becoming increasingly evident after 1925 (Skinner et al. 2006). Very few fires have occurred in the southern California mountains since the onset of fire suppression, although a number of recent, large and severe fires have received attention (e.g., Keeley et al. 2009). Altered fire behavior due to fire suppression and a changing climate has resulted in the replacement of mixed conifer forest by hardwoods and shrubs in some areas burned by stand-replacing crown fires (Goforth & Minnich 2008).

Vegetation

Low and middle elevation shrublands

Mediterranean climate regions like southern California exhibit high levels of plant richness and endemism (Cowling et al. 1996, Underwood et al. 2009). Mediterranean ecosystems are also among those most sensitive to climate and land-use change however, and the fragmented landscapes of southern California may limit the ability of rare and endemic species to shift their ranges in response to climate change (Underwood et al. 2009, Lawson et al. 2010). Where it can, the distribution of vegetation in California is expected to move upslope and poleward in response to climate change (Hayhoe et al. 2004, Loarie et al. 2008, Fellows and Goulden 2012). While such long-term shifts are difficult to observe, observations of short-term shifts in response to drought and climate variability can offer us insight into the trends we are likely to see under warmer and drier climates. Kelly and Goulden (2008) compared a 2006-2007 plant survey to a 1977 survey along a 1.44 mi (2314 m) gradient transect in the Santa Rosa Mountains in southern California. They found the average elevation of the dominant plant species rose approximately 213 ft (65 m) between surveys based on analysis of ten plant species. Fellows and Goulden (2012) measured distribution of live and dead trees in the San Jacinto Mountains of southern California to further explore these patterns. They recorded a 121±108 ft (37 ± 33 m) upslope shift in midmontane species distributions following the 2002-2004 prolonged drought period. Both studies attribute this upward ‘lean’ to small scale climate variability (Kelly and Goulden 2008, Fellows and Goulden 2012), although other authors suggest that for at least some of the observed species, the shift may better be explained by self-thinning (Schwilk and Keeley 2012). Given that climate change in the southwestern U.S. is expected to decrease mean precipitation, increase warming and thereby intensify evapotranspiration and drought (Fellows and Goulden 2012), it is likely that the montane vegetation shifts observed in the studies will be observed on larger spatial and temporal scales in the coming years.

Climate change itself is not the major direct driver of vegetation changes in southern California shrublands. Outside of the direct impacts of expanding urban areas, excessively frequent fire and invasion by exotic plants are at the root of the most obvious changes in vegetation structure and composition in southern California shrublands, and both factors interact with climatic warming and increasing drought. Coastal sage scrub (CSS) and chaparral habitats are being invaded by grasses and forbs from drier parts of Eurasia, and high anthropogenic fire frequencies both abet and are abetted by the presence of these highly flammable invasive species (Keeley et al. 2005, Jacobsen et al. 2009). Climate warming and increasing drought stress reduce native plant vigor and increase mortality, and decrease fuel moistures as well, such that ignitions are more likely to result in fires and fires are more likely to grow large; this in turn increases the magnitude of exotic species invasion, which further contributes to flammability and subsequent invasion (Zedler et al. 1983, Keeley et al. 2012). Many areas of CSS, an important habitat for the endangered California gnatcatcher have been converted to exotic grassland or mixed open CSS and exotic annual grasses, due to increases in fire frequency, grazing, and competitive exclusion of natives by exotic invasive species (Minnich and Dezzani 1998). Shorter fire-return intervals in chaparral habitats have also facilitated invasion by exotic annuals, providing, in turn, positive feedback for more frequent and larger fires (McKenzie et al. 2004). Non-native grass species replace chaparral communities when fires occur more frequently than about every 10 years, due to the time it takes chaparral species to resprout or produce a viable seed bank (Keeley 2006, Syphard et al. 2006, Lombardo et al. 2009). Lippitt et al. (2013) found that in 69% of frequently burned chaparral stands studied in San Diego County (defined as stands that had burned two or more times at intervals of 10 years or less from 1977 to 2003), more than half of the stand was transformed to a disturbed or converted state. Fire return intervals of five years or less in this area were associated with conversion of chamise chaparral to other community types (Lippitt et al. 2013).

Middle and high elevation conifer forests

Fire suppression has been practiced as a federal policy since the early 20th century. In the late 1920’s and early 1930’s, the Forest Service inventoried and mapped vegetation on National Forest lands in California (Wieslander 1935). Minnich et al. (1995) revisited Wieslander plots located in mixed conifer forests on the San Bernardino NF, and found that modern forests were almost 80% denser on average, and mean tree size had greatly decreased; tree composition had also shifted such that shade tolerant species like white fir and incense cedar had replaced pines as the dominant species. Less pronounced increases in density occurred in higher and drier Jeffrey pine-dominated sites. Fellows and Goulden (2012) found disproportionately high rates of mortality in larger trees following an extended drought period, suggesting that interactions between fire suppression and increases in climate stress are likely to further decrease average tree size and increase density of small trees in southern California montane forests. Increases in stand density and warming temperatures have also provided more favorable conditions for bark beetle outbreaks (USFS 2011). Southern California experienced severe mortality due to bark beetle outbreaks in dense stands in 2003-2004, following severe drought (Smith 2007), and increases in drought conditions are likely to increase beetle-caused mortality in the future.

Wildlife

Changes in climate may have both direct (e.g. thermal stress) and indirect (e.g. changes in species interactions and habitat) effects on wildlife distributions and abundances (Martin 2007, Rubidge *et al.* 2011). Direct effects of climate warming are predicted to force species upslope and northward, while indirect effects leave a more complex signature. Studies in other parts of California suggest that wildlife are moving in response to changing climates in order to maintain environmental associations to which they are adapted (small mammals: Moritz et al. 2008, Rubidge et al. 2011; butterflies: Forister et al. 2010; birds: Tingley et al. 2009). Species with a high degree of habitat specialization and/or 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 (Jiguet et al. 2006, Gardali et al. 2012). Breeding birds in southern California shifted their distributions upward on average 377- 410 ft (115-125 meters) over the from 1979 to 2005

(Hargrove and Rotenberry 2011). Most of this shift can be attributed to up-slope encroachment by desert scrub birds rather than range contraction by chaparral birds, suggesting that desert species may be closer to their physiological limits (Hargrove and Rotenberry 2011). Hargrove and Rotenberry (2011) found that climate plays an important role in limiting the lower distributions of (higher-elevation) chaparral bird species in southern California, thus excluding them from low elevation sites, but a less important role in limiting the upper distributions of (lower-elevation) desert bird species. Biotic interactions, such as competition and predation, play a more significant role in limiting the upper distributions of these lower elevation species, further complicating up-slope migrations in response to climate change.

While direct effects of climate change on the Spotted Owl may be positive (positive reproductive output with increases in minimum nesting season temperatures), owl populations in the San Bernardino mountains have been declining in recent years, probably due to indirect effects such as drought, disease, and fire-induced habitat loss, as well as isolation, urbanization, and air pollution (Eliason and Loe 2011, Peery et al. 2012). Another major indirect impact of climate change on wildlife populations is the loss of synchrony between reproductive or migratory phenology and resource availability (MacMynowski and Root 2007, Seavy et al. 2009). Breeding dates of birds like tree swallows have advanced during the last century (in the tree swallow case, they now occur up to 9 days earlier; Dunn and Winkler 1999) which may lead to a mismatch in timing of egg laying relative to availability of food. Shifted flowering, fruiting, and seeding times may affect species that rely on these services. Timing of the migration of California overwintering songbirds like Swainson's Thrush, Warbling Vireo, and Wilson's Warbler among others has also advanced significantly since 1969 (MacMynowski and Root 2007). Asynchrony with animal and insect pollinators may also become a significant problem for Califorrnia plant species (Memmott et al. 2007)

III. Future predictions for trends over the next century linked to climate change

Temperature and Precipitation

As of today, few published climate change or vegetation change modeling studies have been carried out for southern California as a region. Relatively 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 (GCM's) that are used to simulate future climate scenarios. Most GCM's produce raster outputs with pixels that are 10,000's of mi² in area. To be used at finer scales, these outputs must be downscaled using a series of algorithms and assumptions, adding uncertainty to already uncertain data. These finer-scale secondary products currently provide the most credible sources we have for estimating potential outcomes of long-term climate change for California. Another complication is the extent to which GCM's disagree with respect to the probable outcomes of climate change. For example, a comparison of 21 published GCM outputs that included California found that estimates of future precipitation ranged from a 26% increase per 1.8°F (1°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 GCM's predicted warming temperature 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 most recent models (which are considerably more complex and, ideally, more credible) is temperature warming by 9°F by 2100 with precipitation remaining similar or slightly reduced compared to today. Most agree that summers will be drier than they are currently, regardless of levels of precipitation. Tague et al. (2009) summarize that in southern California in particular, temperatures are predicted to increase by 2.7 to 9°F (1.5-5ºC), with small to moderate changes in precipitation ranging from negative (-30%) to slightly positive (+10%). Predictions for southern California also include an increase in winter rains, followed by drier summers (Field et al. 1999, Gabet and Dunne 2003).

The most widely cited of the recent modeling efforts in California is probably Hayhoe et al. (2004). Hayhoe et al. (2004) used two contrasting GCM's (much warmer and drier 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 snowfall 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° F 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, ranged from -3.6 in to 6.2 in (-91mm-157mm); the remaining scenario predicted a 1.5 in (38 mm) increase.

Cayan et al. (2008) uses two climate models; the Parallel Climate Model (PCM1) from the National Center for Atmospheric Research and the Department of Energy, and the Geophysical Fluid Dynamics Laboratory CM2.1 (GFDL) from the National Oceanic and Atmospheric Administration to investigate possible future climate changes in California. Although the findings indicated that over the next century temperatures are generally predicted to increase while precipitation is predicted to remained fairly stable, the complex California landscape will require finer scale GCM information than is presently available.

The recent study by the Bureau of Reclamation (BOR) used downscaled Coupled Model Intercomparison Project Phase 3 (CMIP3) climate projections to predict future impacts in the Santa Ana river watershed. The study projects increases in temperature of 4.1°F by 2070. The number of extreme heat days per year (days > 95 °F) is predicted to increase dramatically as well during this time period, for example from 9.6 to 43 extreme heat days in the city of Riverside (Blickenstaff et al. 2013). The study also found that lower precipitation is likely for the majority of the watersheds except for the San Gabriel watershed, with the majority of precipitation occurring during extreme infrequent events (website link; initial presented results), resulting in unreliable precipitation and high intensity storms. BOR Projections include reductions by 8% in annual precipitation, 93% in April 1st snow-water-equivalent, and 15% in annual runoff by 2070 (Blickenstaff et al. 2013). Snowpack levels at Big Bear are expected to decline by 70% of 1990 snowpack levels by the year 2070 (Blickenstaff et al. 2013).

Using more local-scale models, Hughes et al. (2011) projected an increase in temperature between the 20th and 21st century for the interior desert of southern California, associated with transient climate change of anthropogenic origin. The projected increase in minimum winter temperatures in the desert would cause a decrease in the temperature gradient between the cold desert and warmer air over the ocean, leading to a reduction in the duration and frequency of Santa Ana events during this time span (Hughes et al. 2011). However, Hughes et al. (2011), also predict increased temperature and decreased relative humidity during this same time period, leaving to mixed impacts on local climate and wildfire.

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. In the Santa Ana river basin, annual runoff is projected to decrease by 15% by 2070, winter and early spring runoff is projected to initially increase (10% by 2020), and then decrease by 6% of 1990 average by 2070, and late spring/summer runoff is projected to decline by 32% between 1990 and 2070 (Blickenstaff et al. 2013). 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). Less well understood are the potential changes to river-fed streams, which are much more common in southern California. 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). Snowfall in the greater Los Angeles area is projected to decline by 30-42% by mid-century, and 30-60% by the end of the century, dependent on mitigation employed, with greater loss at lower elevations (Fengpeng et al. 2013).

While hydrological changes in snow-dominated areas like the Sierra Nevada, and the higher mountain ranges of southern California will mainly depend on shifts in precipitation patterns, vegetation shifts may play a more central role in changes to southern California hydrology (Tague et al. 2009). Hydrology in semi-arid Mediterranean type ecosystems is largely dependent on climate-vegetation-soil-water interactions, which can vary strongly with temperature and CO_2 levels (Tague et al. 2009). Increased temperatures alone will likely reduce net primary productivity (NPP) in Mediterranean ecosystems (Penuelas et al. 2007). This reduction in NPP would lead to reduced water use, potentially leading to a moderate increase in summer streamflow (Tague et al. 2009). However, when modeled with the increase in CO_2 levels that are driving climate change, impacts of CO_2 will lead to higher biomass and NPP in chaparral ecosystems, and thus higher water consumption, probably far outweighing the losses due to temperature (Tague et al. 2009). Frequency of low streamflow years is projected to be considerably higher with greater levels of atmospheric CO_2, and NPP is projected to more variable from year to year (Tague et al. 2009). Additionally, rainfall is predicted to occur in higher concentrations in fewer events leading to higher variability and unreliability in meteoric, stream and ground water in a region already subject to the most variable precipitation regime in North America (Dettinger et al. 2011). Warming temperatures are also expected to extend the period of summer drought, and decrease flows in the dry months (Reba et al. 2011). Increased water demand, extended drought periods, and high precipitation variability are likely to increase ecosystem vulnerability in a changing climate.

While vegetation-temperature-CO_2 interactions will play a central role in low-flow shifts, fire may play a central role in high-flow shifts under future climate change (Tague et al. 2009). Increases in fire frequency (see fire section below) are likely to lead to increased streamflow, sediment load, and peak discharges in chaparral ecosystems (Florsheim et al. 1991, Loaiciga et al. 2001, Tague et al. 2009). Increases in fire frequency are likely to decrease plant cover, which in turn will decrease water infiltration into soil, increase surface flow, and lead ultimately to increased soil erosion (Riera et al. 2007). In addition, while overall rainfall may decrease in the coming century, as rainfall occurs in fewer, more intense events, vegetation will not be able to hold onto water as it arrives, further intensifying high-flow and flooding events (Vallejo et al. 2012). Blickenstaff et al. (2013) project significantly increased flooding risk in the Santa Ana river watershed, including an increase in streamflow rates from 134,000 cfs to 239,000 cfs between 1990 and 2070, and what was historically a 200-year flood event becoming a 70-year event by 2070. Increases in extreme hydrologic events across the western U.S. are predicted to be especially pronounced in California (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 variability in streamflow in California is already resulting in – and is predicted to continue to result in – extended wet and dry spells (Pagano and Garen 2005), with significant economic, social, and biological impacts (Mote et al. 2005).

Changes in vegetation patterns in southern California may further alter the patterns and magnitude of erosion and runoff. Gabet and Dunne (2003) reported that sediment delivery is 38% higher under grassland than coastal sage vegetation conditions in an area of the Transverse Range just north of Santa Barbara, CA. However, in coastal sage, most sediment is delivered by catastrophic processes like slumps, landslides, and debris flows, strongly linked to the occurrence of fires, while soil creep accounts for most sediment delivery in grassland systems (Gabet and Dunne 2003). Thus, not only would runoff and erosion rates be higher with vegetation conversion, but the method of delivery would be altered from ‘catastrophic to chronic’ (Gabet and Dunne 2003).

Fire

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 (Pausas 2004, Spracklen et al. 2009, Guyette et al 2012). Westerling and Bryant (2008) predict a 10-35% increase in large fire risk by midcentury in California and Nevada, and Westerling et al. (2011) projected increases in burned area of up to 2.5 times the current levels in southern California shrublands and forestlands by the end of the century (at the same time, areas of desert vegetation are projected to decrease in flammability due to drier growing seasons; Fig 7).

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 coniferous forests in the semiarid American West have led to fuel-rich conditions in some habitat types 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. 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. 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 in the coniferous forests types.

Predictions for southern California include both increases and decreases in Santa Ana winds, depending on the study (Field et al. 1999, Gabet and Dunne 2003, Hughes et al. 2011), but perhaps more importantly, Miller and Schlegal (2006) project shifts in timing of these dry, offshore winds from September-October to November-December. Drier summers and increases in high-wind fire weather conditions during late season critically dry periods, coupled with growth in human ignitions, would be likely to increase the frequency and intensity of fires in the region (Field et al. 1999, Gabet and Dunne 2003, Miller and Schlegal 2006). Davis and Michaelsen (1995) predict a 17% decrease in the fire return interval for central coastal California (Gabet and Dunne 2003). Grassland fuels are flashier than shrubland fuels, making both ignition and rapid spread more likely in. Thus if conversion of shrublands to grasslands continues as predicted, we may expect larger, more frequent fires in the southern California National Forests (Minnich and Dezzani 1998).

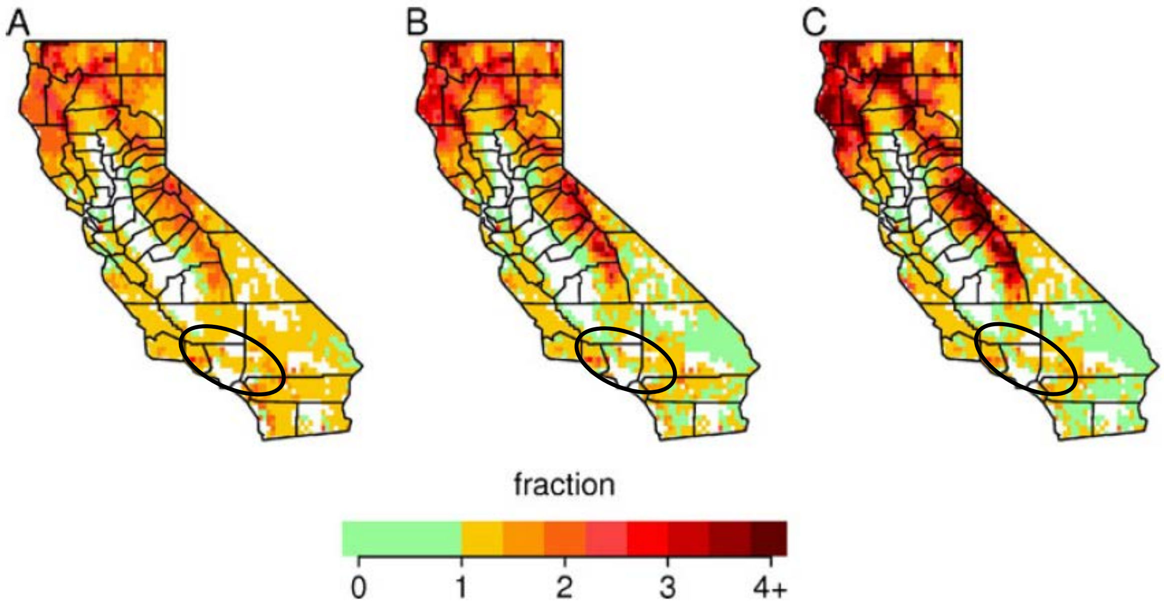


Figure 7. Proportional change in projected mean annual area burned for the 2050-2099 period relative to the mean annual area burned for the reference period (1950-1999) for three climate change scenarios. “1” = unchanged; “2” = 2x the reference condition, etc. A represents the NCAR PCM1 climate scenarios (warmer and slightly drier than today): B = CNRM CM3 scenario (drier and much warmer than today); C = GFDL CM2.1 scenario (much warmer and much drier than today). ANF-BDF area is circled. Figure from Westerling et al. (2011).

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 (38.6 mi^2) cells. To 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 ANF/BDF 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 PCM-A2, their most neutral future scenarios, Lenihan et al. (2003, 2008) projected a general expansion of grassland and some expansion of mixed evergreen woodland in southern California. With higher nighttime minimum temperatures, broadleaf trees (especially oak species) were predicted to replace conifer-dominated forests. Under their drier future scenarios, Lenihan et al. (2003, 2008) predicted that grasslands would expand, and that shrub and tree-dominated vegetation would decline (Fig. 8). 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 California coastal area may replace much of the shrubland with grassland (Fig. 8), continuing an historical trend. 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.

Coupled climate-vegetation models predict the expansion of savanna grassland communities at the expense of shrublands in California foothills (Field et al. 1999). Over the next century, grassy savanna communities may replace shrublands entirely in the Coast Ranges of southern California (Field et al. 1999, Gabet and Dunne 2003; Fig. 9). Damage from pollutants like ozone and nitrogen oxides may be interacting with changes in climate and fire patterns to cause expansion of exotic grasslands into current shrublands in areas like Riverside and San Diego counties (Field et al. 1999).

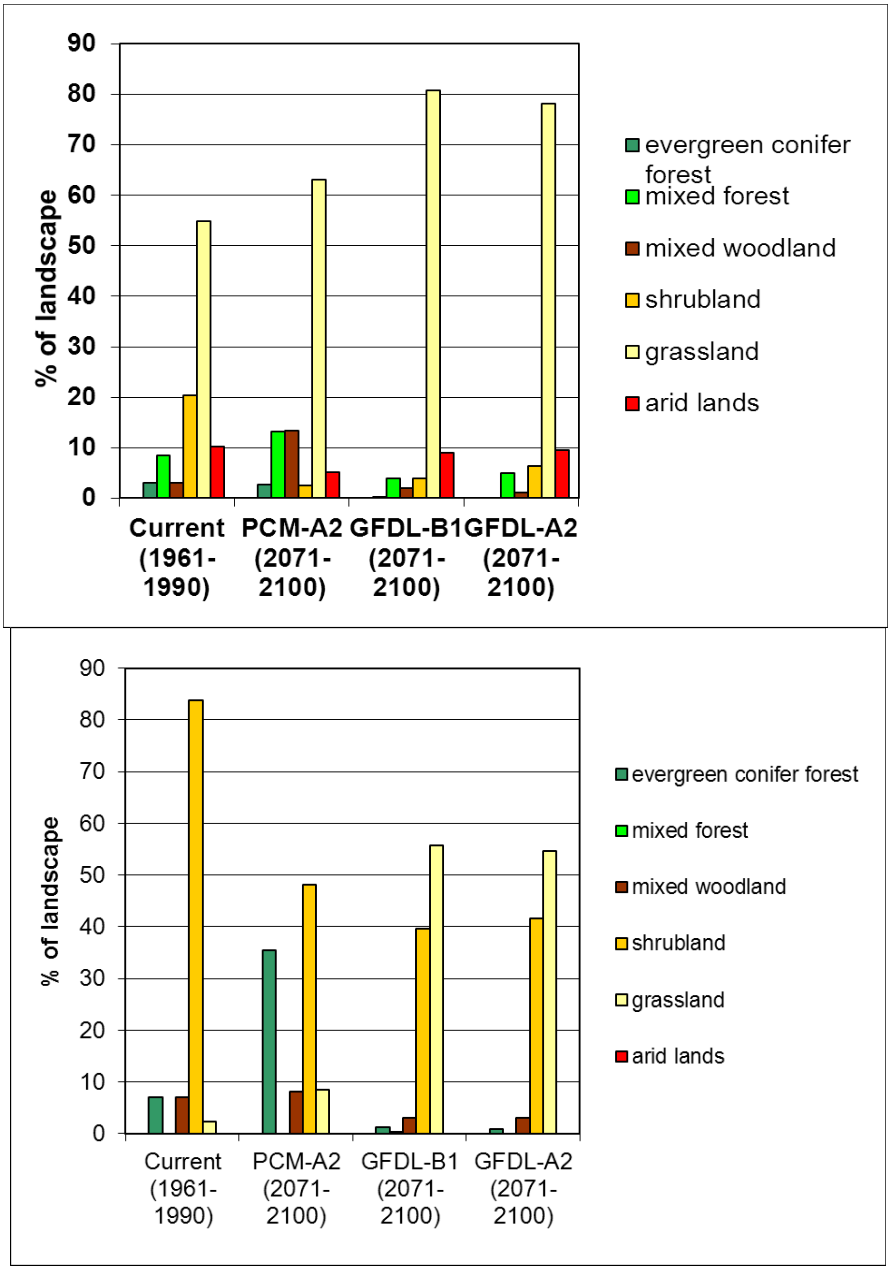


Figure 8. Current vs. future projections of vegetation extent for the Southern California Mountains & Valleys Section (top), and the Southern California Coast Section (bottom). Original data from Lenihan et al. (2008). The PCM-A2 = similar ppt. to today, with <5.5°F temp. increase; GFDL-B1 scenario = moderately drier than today, with moderate temperature increase (<5.5° F); GFDL-A2 = much drier than today and much warmer (>7.2° higher). All scenarios project loss of shrubland and increase in grassland.

Endemic plant species that specialize in uncommon or sparsely distributed habitat (e.g. gabbro soils, montane meadows) will have difficulty responding to changing climatic conditions by migrating (Conlisk et al. 2013). Such narrowly distributed species are also at high risk due to disturbances like fires or floods that may extirpate entire populations. Climate induced reductions in suitable habitat may also disproportionately affect long-lived obligate seeding shrubs which are sensitive to changes in temperature and drought severity (Lawson et al. 2010). Lawson et al. (2010) predicted suitable habitat loss of between 70% and 95% for the obligate seeder *Ceanothus verrucosus* in southern California in the coming century. In addition to habitat loss due to changes in temperature and precipitation, such species may suffer further declines if fire return intervals fall below 20 years (Lawson et al. 2010) which seems likely to occur given the combination of climate warming and human population growth that southern California is experiencing. High fire frequency can have multiple negative effects on Mediterranean type shrublands, including: preventing obligate seeding species from replenishing seed banks; depleting starch reserves in resprouting species; and favoring weedy or invasive species (Pausas 2004).

Wildlife

Significant changes in California’s terrestrial fauna and flora are projected over the next century due to climate change effects on temperature, precipitation, and resulting habitat distributions. Stralberg et al. (2009) developed current and future species distribution models for 60 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. A total of 128 out of 358 (36%) of California’s bird species of “special concern” (rare, threatened, endangered, or experiencing significant decline; Shuford and Gardali 2008) were ranked as vulnerable to climate change, including the western yellow-billed cuckoo, gray vireo, cactus wren, and willow flycatcher (Gardali et al. 2012). For aquatic species like the Steelhead, decreases in August streamflow likely to be caused by increased CO_2 levels associated with climate change could have negative implications for habitat suitability and availability (Tague et al. 2009). Based on bioclimatic models, Lawler et al. (2009a,b) projected high vulnerability of California’s amphibian fauna (>50% change in species) and moderate vulnerability of California’s mammalian fauna (10-40% change) under a high greenhouse gas emissions scenario by the end of the century. In a similar study, Loarie et al. (2008) projected that 2/3 of California’s native flora will experience >80% reduction in range size by 2100. Preston et al. (2008) predict decreases in suitable habitat for the endangered Quino Checkerspot butterfly and threatened California Gnatcatcher of between 12% and 100% depending on the climate model. Suitable habitat was predicted to shift eastward in southern California, toward higher elevations. Some invasive species, like the argentine ant, are limited in distribution in southern California by night-time-minimum temperatures (Menke et al. 2007). Increasing minimum temperatures will likely facilitate the spread of argentine ants, leading to decreases in native ant diversity, with cascading impacts (Menke et al. 2007). Thus, we are likely to see an overall decrease in suitable habitat for some native wildlife species, coupled with increased suitability for some invasive species, leading to potential changes in animal community composition in southern California National Forests.

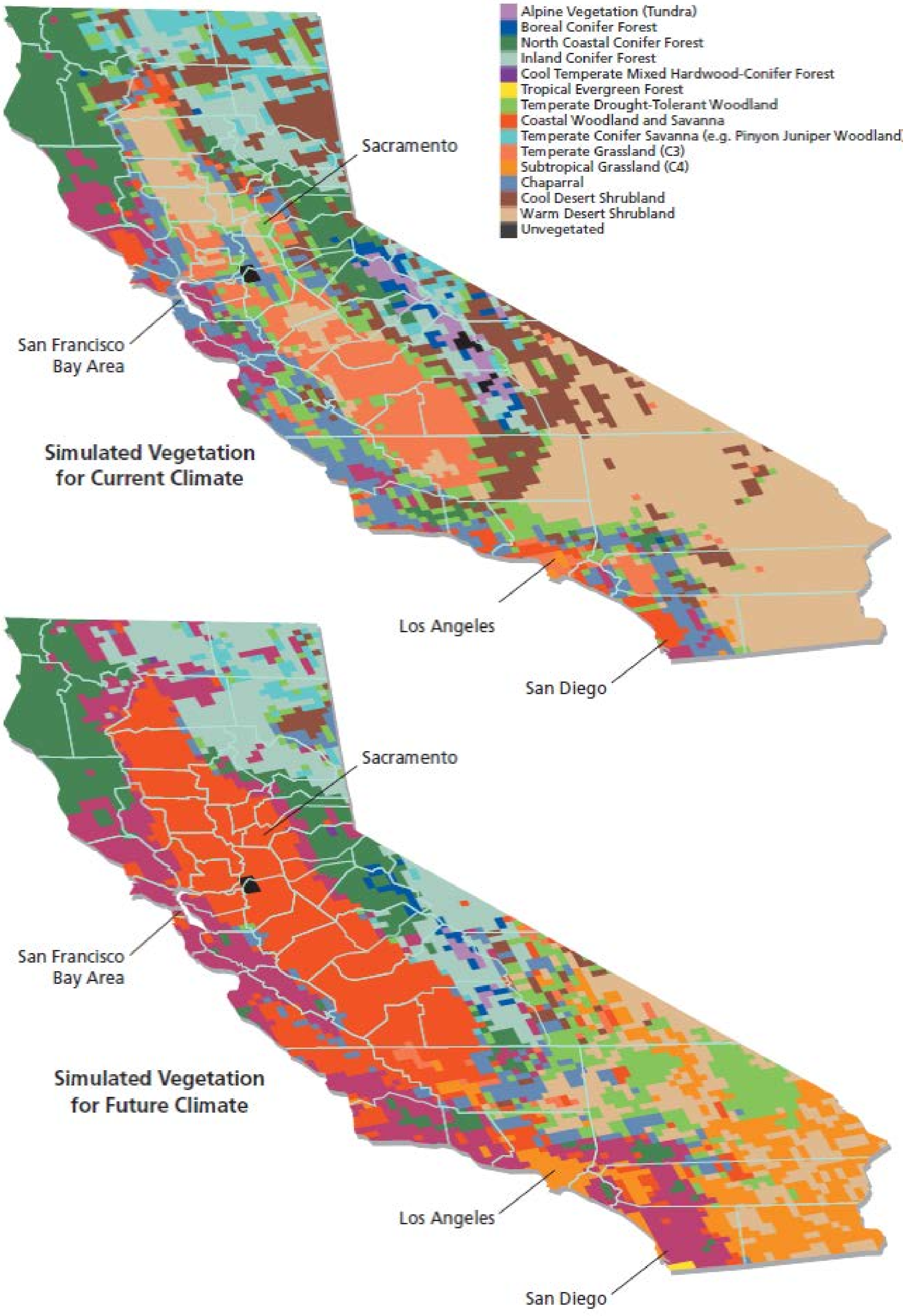


Figure 9. Figure from Fields et al. 1999 (pg 28). Projected vegetation of California. Top map represents shows vegetation in California, and bottom map shows projected vegetation in 2099 using MAPSS model. Southern California projections show much replacement of shrubland and chaparral by grassland.

Hydrologic effects of climate change will likely alter wildlife species interactions. Those aquatic species with a competitive advantage in colder waters will likely suffer losses due to both thermal stress and increased competition as water temperatures rise (Rahel et al. 2008, Kennedy et al. 2009). Increasing water temperatures may favor invasive fish species like carp and bass that survive well in warmer streams, while threatening native species like steelhead and mountain yellow-legged frogs that require cooler water streams. Additionally, sensitive benthic invertebrate populations may also be reduced by increases in stream sediment caused by more frequent large and severe wildfires that are likely to be associated with climate warming (Oliver *et al.* 2012). Larger effects will likely be observed in smaller streams (Oliver *et al.* 2012).

While wildlife species are expected to shift their distributions in response to changing climate and habitat availability, this may be challenging for many species in southern California, where urban and exurban development have led to pronounced habitat fragmentation. With diminished ability to migrate, wildlife species may not be able to follow shifts in the vegetation on which they depend for habitat or food resources, or may be trapped in areas where their food sources begin to decline. For example, predators like mountain lions require the spatial complexity of shrublands and/or forests for cover to move, sleep, and hunt and they actively avoid grasslands (Burdett et al. 2010, Ordenana et al. 2010). Thus, they may suffer declines in the southern California National Forests, where they are already threatened by habitat loss and fragmentation, if the proportion of grassland habitat increases in accordance with projections. Species that rely on berries, acorns or conifer seeds as a food source may suffer in areas where source plant species produce less food due to climate stress. Species like the desert bighorn sheep, which already have small populations and limited habitat, will be particularly sensitive to added stressors brought on by climate change, including thermal stress, potential reduction in food sources, and shifts in suitable habitat areas (Epps et al. 2004). Results of the thermal, hydrologic, and habitat changes associated with climate change in this fragmented landscape may lead to ever increasing risk of extirpation of small, isolated populations of wildlife.

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Appendix A. Weather Station Information

Weather stations were selected for inclusion based on their location relative to the ANF/BDF Forests and the length and completeness of their records. Stations with the longest records are Pasadena and San Bernardino, California. These two stations are located in the metropolitan valley adjacent to and south of the ANF/BDF forests. Fairmont and Palmdale, California stations are located in the desert north of the ANF at mid-elevations. The remaining three stations are located in the mountain areas within the National Forests. Temperature and precipitation data collection periods ranged from 63 to 111 years (with between 1 and 23 years missing data). See Table A1 for station locations relative to the ANF and BDF, the data range and completeness of meteorological data.

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 was 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 that 70% complete.

Table A1. Weather Station Summary Information

Station	Elev. (Feet)	Latitude	Longitude	Proximity to National Forest	Data range	Years of excluded data (Temp/Ppt)
Pasadena	0860	34° 08' N	118° 08' W	4 mi south ANF	1909-2012	1/13
San Bernardino	1170	34° 08' N	117° 16' W	6 mi south BDF	1893-2004	3/23
Fairmont	3060	34° 43' N	118° 26' W	adjacent north ANF	1922-2012	4/20
Palmdale	2660	34° 35' N	118° 07' W	8 mi north ANF	1933-2012	1/5
Idyllwild	5380	33° 45' N	116° 43' W	within BDF	1946-2012	6/9
Mt Wilson No. 2	5710	34° 14 N	118° 04' W	within ANF	1949-2012	4/10
Lake Arrowhead	5200	34° 14' N	117° 11' W	within BDF	1942-2007	5/12