A summary of current trends and probable future trends in climate and climate-driven processes for the Shasta-Trinity National Forest and surrounding lands

Ramona J. Butz, Northern Province Ecologist, USDA Forest Service, Pacific Southwest Region. rbutz@fs.fed.us; 707-441-3584*

Sarah Sawyer, Assistant Regional Ecologist, USDA Forest Service, Pacific Southwest Region.

Hugh Safford, Regional Ecologist, USDA Forest Service, Pacific Southwest Region.

Last Update: December, 2015

Contents

I. Introduction

This summary of climate and climate-driven trends in northern 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 Shasta-Trinity National Forest and surrounding lands in northern 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weather station data, PRISM data, and published literature; in some instances, important and credible findings from unpublished studies are also included.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 represents an update of our original climate trend summary for 2010. Further updates are planned at approximately 5-year intervals.

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 five weather stations in the vicinity of the Shasta-Trinity National Forest (WRCC 2015). 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 Shasta-Trinity National Forest and the length and completeness of their records. For details on weather stations selected and station data analysis, see Appendix A. Our analysis is supplemented with historic trends in temperature and precipitation derived using spatial data from the PRISM climate dataset (Daly et al. 1994) and compiled by Rapacciuolo et al. (2014) (Figures 1 & 4).

Temperature and Precipitation

Temperature

California is currently (2012-2014) experiencing the hottest and driest period in its recorded climate history (i.e., since 1895) (Mann and Gleick 2015). The magnitude and direction of temperature change are variable across the state and depend on the time series in question. For example, there was an order of magnitude increase in warming between 1970-2006 when compared to 1918-2006, indicating accelerated warming in the last 35 years in California (Cordero et al. 2011). A straightforward and recent summary of these trends is presented in Rapacciuolo et al. (2014) and broken down by ecoregion. The authors report an average statewide temperature increase of 0.81° F (0.45° C) between historic (1900-1939) and modern (1970-2009) times. The Northwestern California ecoregion, which includes the Shasta-Trinity National Forest, shows an increase in mean (0.32° F, 0.18° C) and minimum (0.85° F, 0.47° C) temperature and a decrease in maximum (-0.41° F, -0.23° C) temperature over this same time period (Rapacciuolo et al. 2014).

All five weather stations exhibit significant increases in temperature over their periods of record (Table 1, Figure 2). At each of the stations, the increases are being driven by a significant increase in mean minimum (i.e., nighttime) temperatures, which have risen by between 1° and 2.5° F (Table 1, Figure 2). The increase in minimum mean (nighttime) temperature when compared to mean and maximum mean (daytime) temperatures are consistent with findings across California (Cordero et al. 2011, LaDochy et al. 2007) and the globe (Vose et al. 2005). Significant increases in nighttime temperatures have also been observed at several stations on the Mendocino, Klamath, and Six Rivers National Forests. In addition to increases in nighttime temperatures, significant increases in maximum mean (daytime) temperatures were observered at the Shasta Dam, Whiskeytown Reservoir, and McCloud weather station (Table 1, Figure 2).

The occurrence of nighttime freezing temperatures is steady or decreasing at all available stations, with a significant decrease observed at the Weaverville station (Table 1, Figure 3). At the beginning of the Weaverville data record, approximately four and a half months per year could be expected to have average nighttime temperatures that fall below freezing. Today the average is over three, and the trend is decreasing.

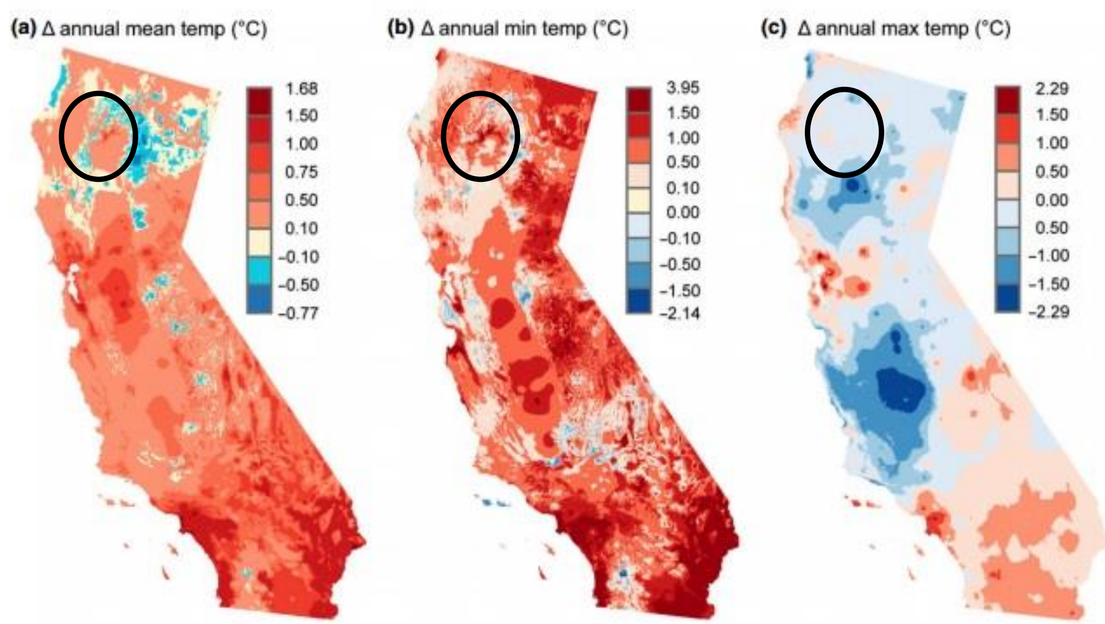
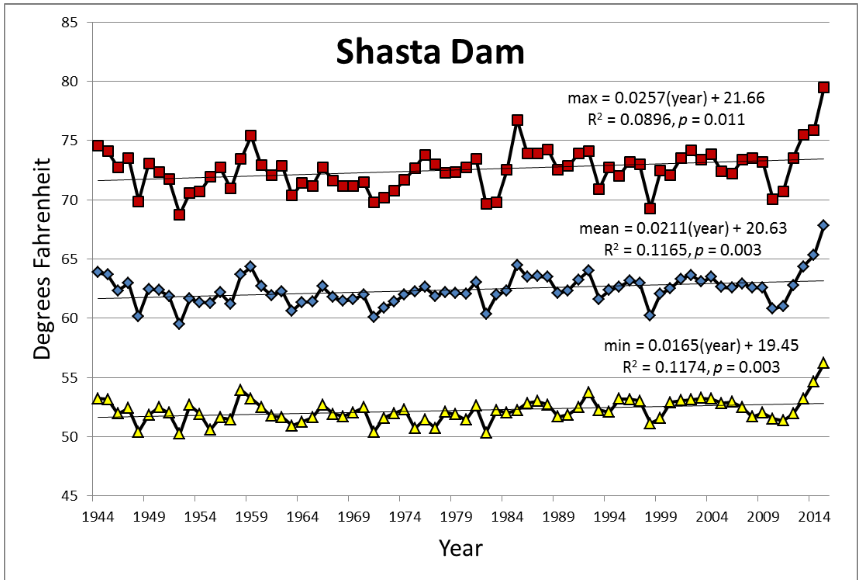
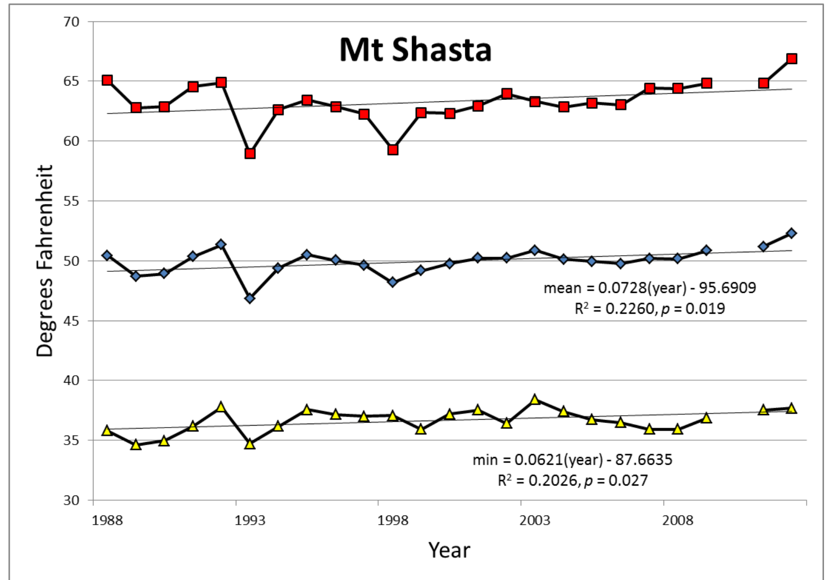


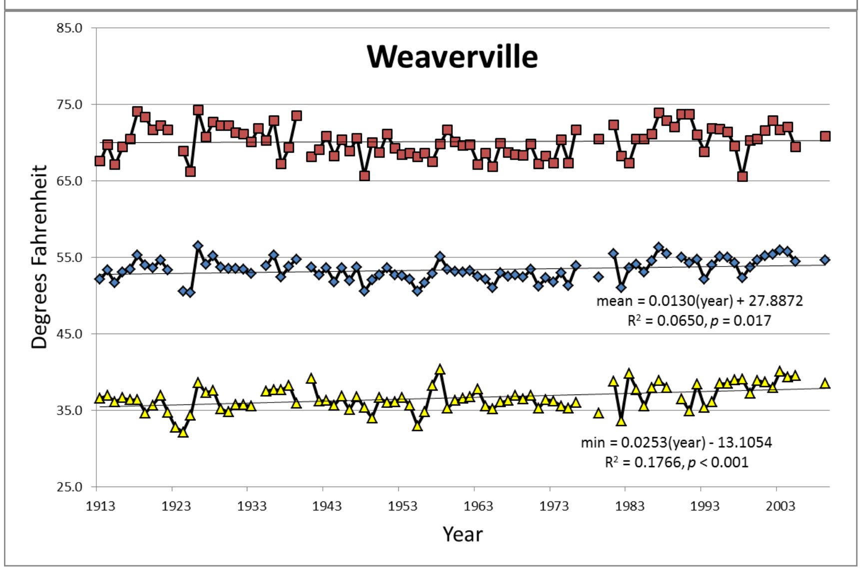
Figure 1. Spatial representation of differences in A) annual mean, B) annual minimum and C) annual maximum temperature (°C) between historic (1900-1930) and modern times (1970-2009). Black circles represent the vicinity of the SHF. Figures from Rapacciuolo et al. 2014.

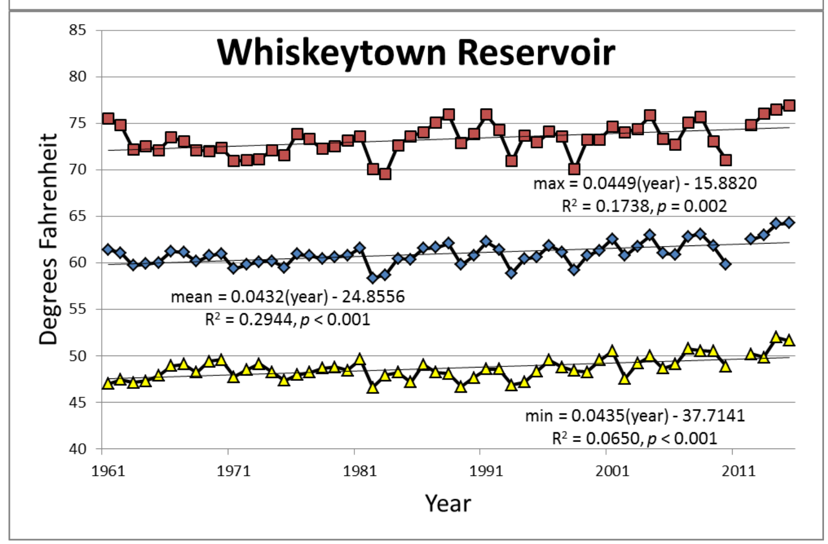
Table 1. Direction, magnitude and statistical significance of climatic shifts at five weather stations in the area of the Shasta-Trinity National Forest. Numerical values indicate the difference between the expected values for the earliest and most recent years of the given time frame, as calculated 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.**

	Shasta Dam	**Weaverville**	**Whiskeytown**	**McCloud**	**Mt Shasta**
Elevation	**1070 ft (326 m)**	**2050 ft (625 m)**	**1310 ft (399 m)**	**3280 ft (1000 m)**	**3590 ft (1094 m)**
Temperature					
Mean (°F)	+1.5**	+1.2*	+2.3***	+1.9***	+1.7*
Max. (°F)	+1.8*	ns	+2.4**	+1.5*	ns
Min. (°F)	+1.2**	+2.4***	+2.3***	+2.2***	+1.5*
Freezing (mo/yr)	ns	-0.8**	ns	ns	ns
Precipitation					
Total (in.)	ns	Incomplete data	ns	ns	ns
Coefficient of variation	ns	Incomplete data	ns	+23.8	ns
Snowfall (in)	-12.1*	Incomplete data	ns	-69.4***	Incomplete data


Shasta Dam
max = 0.0257(year) + 21.66
R² = 0.0896, p = 0.011
mean = 0.0211(year) + 20.63
R² = 0.1165, p = 0.003
min = 0.0165(year) + 19.45
R² = 0.1174, p = 0.003
Degrees Fahrenheit
Year


Mt Shasta
mean = 0.0728(year) - 95.6909
R² = 0.2260, p = 0.019
min = 0.0621(year) - 87.6635
R² = 0.2026, p = 0.027
Degrees Fahrenheit
Year


Weaverville
mean = 0.0130(year) + 27.8872
R² = 0.0650, p = 0.017
min = 0.0253(year) - 13.1054
R² = 0.1766, p < 0.001
Degrees Fahrenheit
Year


Whiskeytown Reservoir
max = 0.0449(year) - 15.8820
R² = 0.1738, p = 0.002
mean = 0.0432(year) - 24.8556
R² = 0.2944, p < 0.001
min = 0.0435(year) - 37.7141
R² = 0.0650, p < 0.001
Degrees Fahrenheit
Year

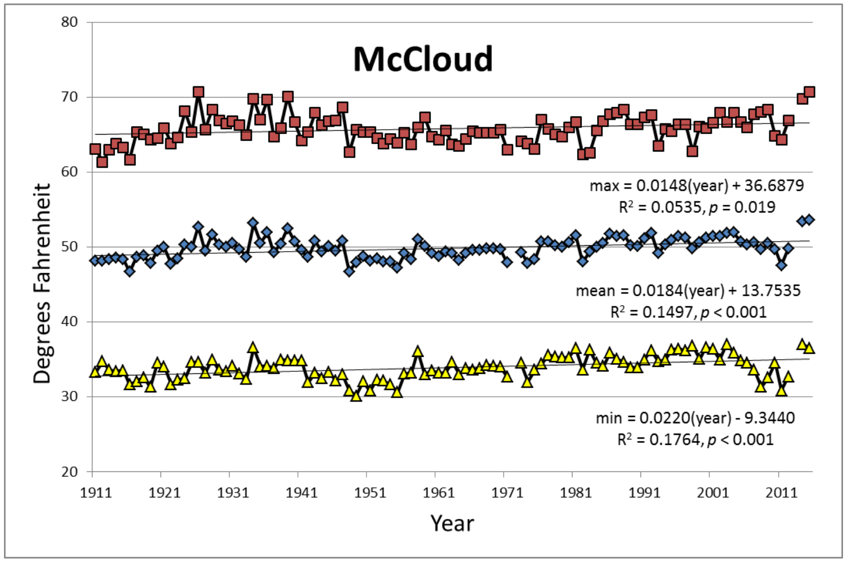


Figure 2. Annual mean, mean maximum, and mean minimum temperatures at five weather stations. Linear regression equations, coefficients of determinations, and statistical significance shown for significant regressions only. No transformations were employed. Data from WRCC 2015.

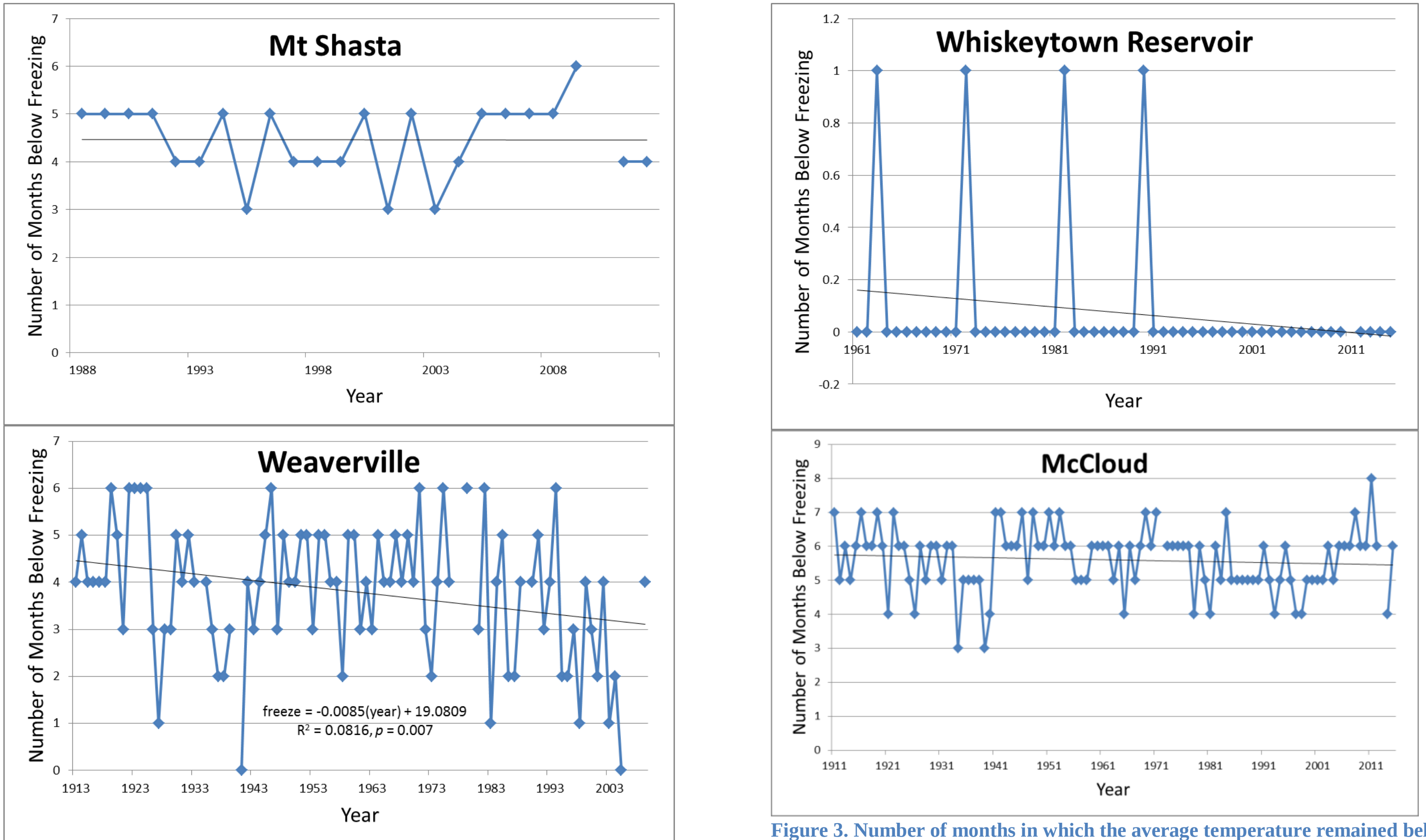


Figure 3. Number of months in which the average temperature remained below freezing for four weather stations. Linear regression equations, coefficients of determination and statistical significance shown for significant regressions only. No transformations were employed. Data from WRCC 2015.

Precipitation

Since 2012, California has experienced a record setting drought that includes the lowest yearly precipitation on record (Diffenbaugh et al. 2015). Tree ring data suggest that the 2012-2014 drought is the most severe in the past 1,200 years (Griffin and Anchukaitis 2014). While the precipitation deficits beginning in 2012 are not unprecedented in the paleoclimate, when coupled with rising temperatures, the current drought stands out as the most severe since perhaps the 9th century (Griffin and Anchukaitis 2014). Despite the current drought conditions, climate data analyzed by Rapacciuolo et al. (2014) suggesting long-term slight to moderate increases in precipitation in the vicinity of the SHF (Figure 4) is supported by precipitation trends from the four weather stations with available precipitation data on and adjacent to the SHF (Table 1).

There are no statistically significant changes in mean annual precipitation at any of the four weather stations analyzed (Table 1, Figure 5). There is very high interannual variability in all five precipitation records, such that the value predicted by the regression line in each figure is rarely representative of the actual annual mean. There were no significant increases in seasonal precipitation at any station, and the distribution of precipitation across the year has remained similar through the record.

The 5-year coefficient of variation of annual precipitation is statistically steady at three of the four stations, with qualitative increases at the Shasta Dam and Whiskeytown Reservoir stations and a qualitative decrease at the Mt. Shasta station (Table 1, Figure 6). A highly significant increase in the coefficient of variation at the McCloud station was observed over the period from 1928-2003. An increasing coefficient of variation in annual precipitation demonstrates that year-to-year variability in precipitation has increased over the course of the last century, while a steady coefficient of variation denotes that year-to-year variability remains relatively stable.

For the three stations with available snowfall records, all show declining trends in annual snowfall, with significant decreases at Shasta Dam and McCloud of 12 and 69 inches respectively (Table 1, Figure 7). Snowfall data for Weaverville and Mt. Shasta were too incomplete to allow for analysis.

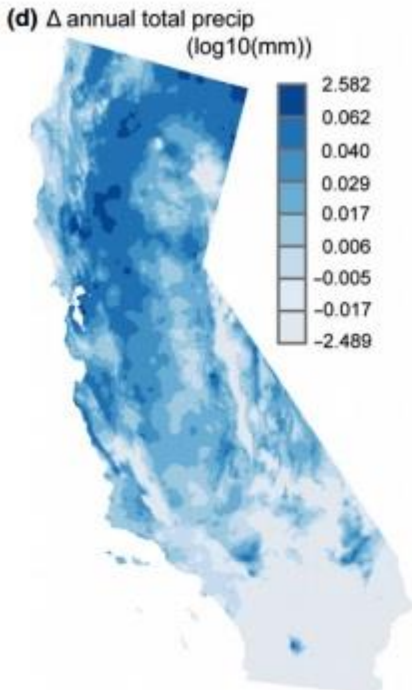


Figure 4. Spatial representation of difference in total annual precipitation between historic (1900-1930) and modern times (1970-2009). Figures from Rapacciuolo et al. 2014.

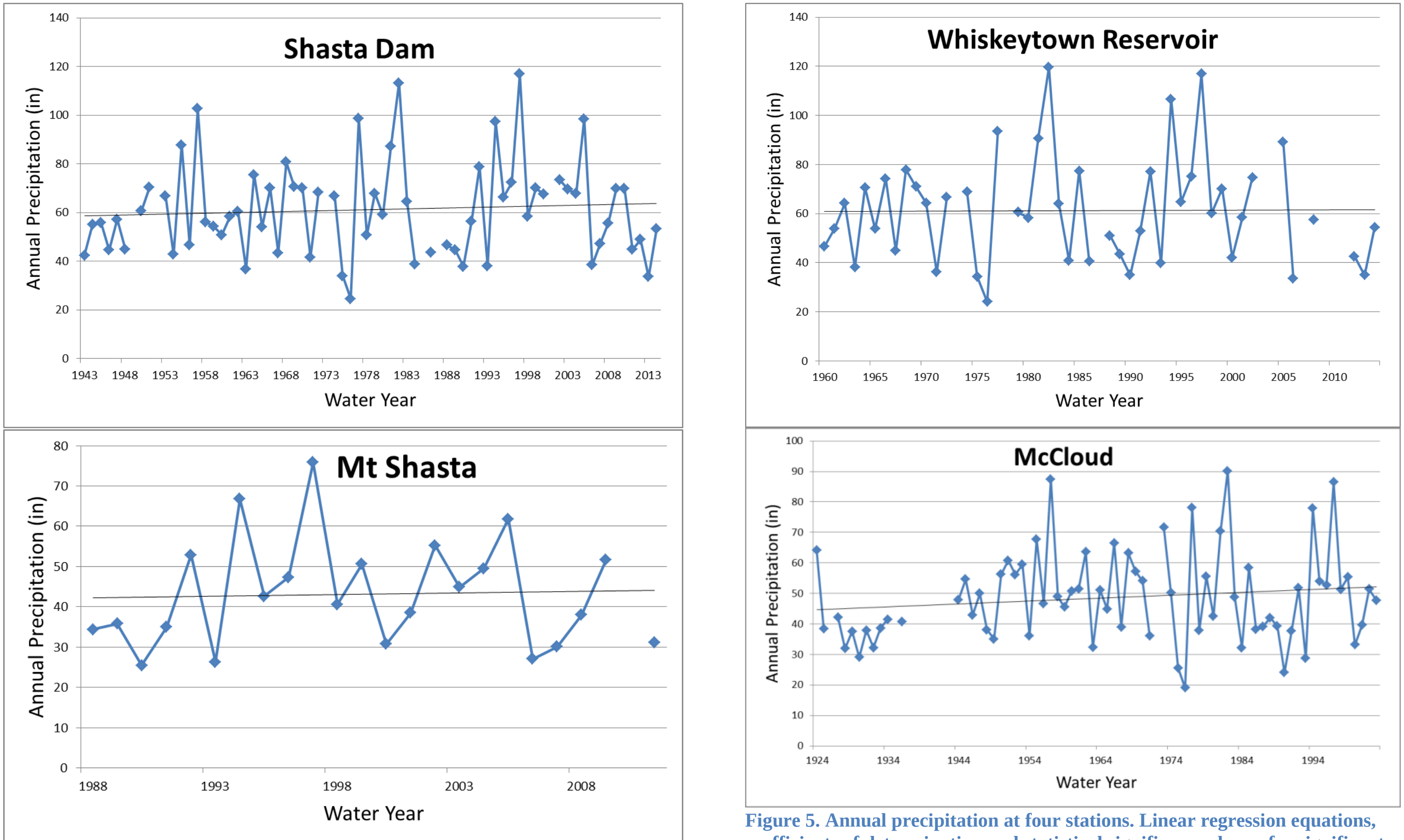


Figure 5. Annual precipitation at four stations. Linear regression equations, coefficients of determination and statistical significance shown for significant regressions only. No transformations were employed. Data from WRCC 2015.

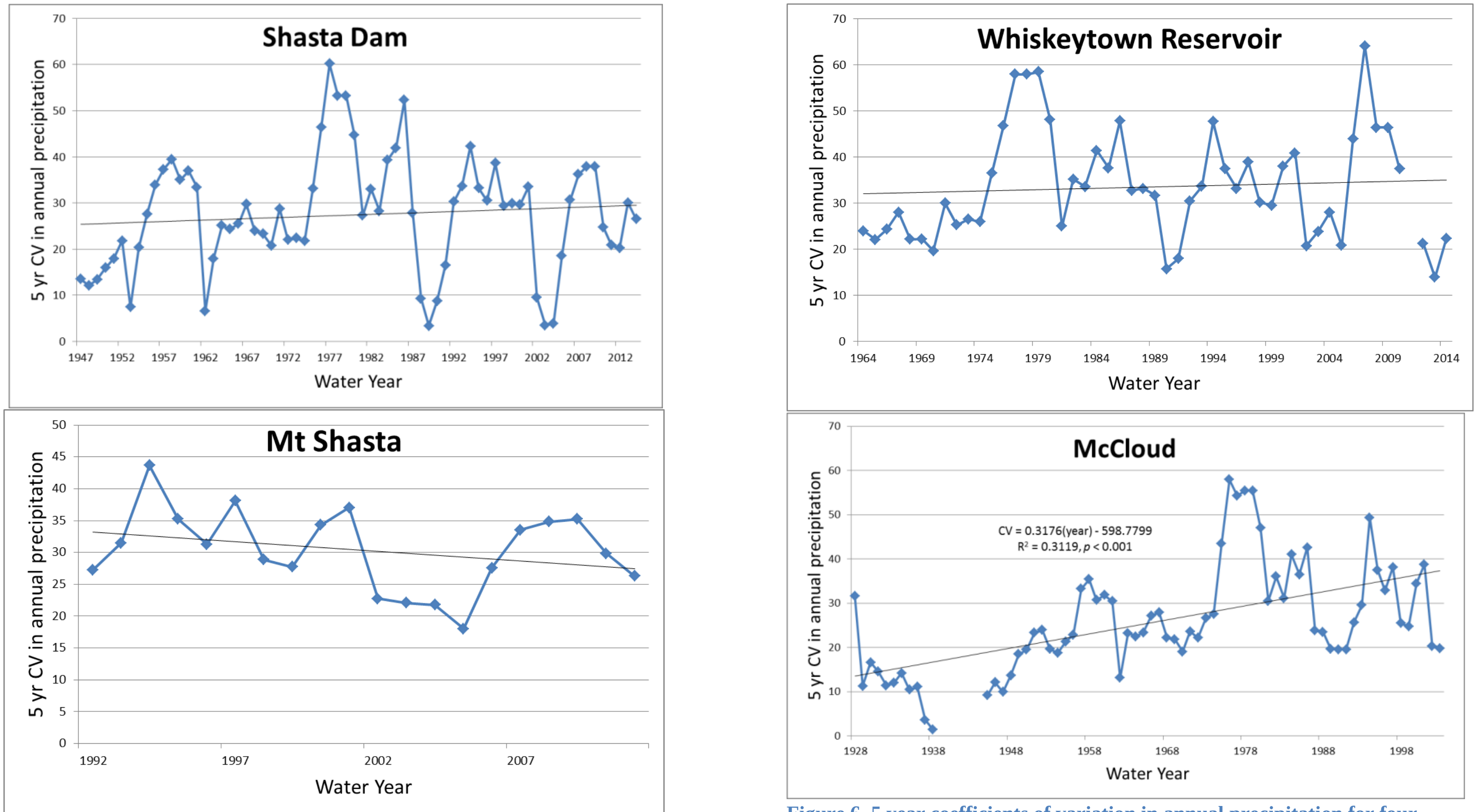


Figure 6. 5 year coefficients of variation in annual precipitation for four weather stations. Regression equations, coefficients of determination, and statistical significance shown for significant regressions only, indicate a mix of increasing and decreasing variability of precipitation over time. No transformations were employed. Data from WRCC 2015.

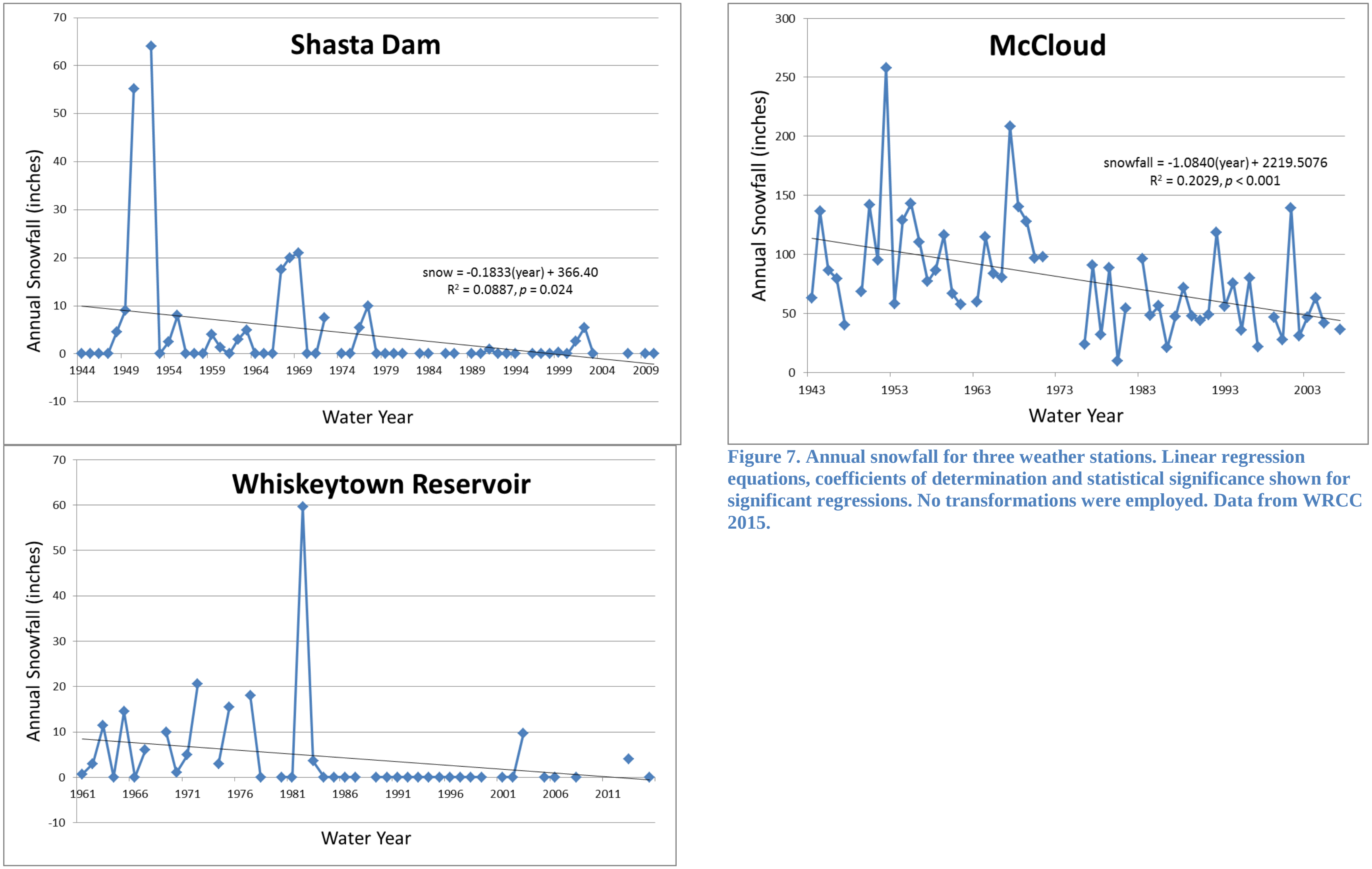


Figure 7. Annual snowfall for three weather stations. Linear regression equations, coefficients of determination and statistical significance shown for significant regressions. No transformations were employed. Data from WRCC 2015.

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). Analyses of hydrometeorological data from the lower Klamath Basin show a decrease in the percentage of precipitation falling as snow and accelerated snowpack melt, resulting in earlier peak runoff and lower base flows (Hamlet et al. 2005; Mote et al. 2005; Regonda et al. 2005; Stewart et al. 2005; Mote 2006; Van Kirk and Naman 2008). 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 2003, 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. Trends in April 1 snow water equivalent (SWE) appear to be driven by temperature, which is mostly a function of elevation and latitude (Knowles and Cayan 2004; Mote 2006), and secondarily by precipitation (Hamlet et al. 2005; Mote et al. 2005; Stewart et al. 2005).

Stream gauge data and climate stations in northwestern California show that summer low flows have decreased and summer stream temperatures have increased in many of northern California's coastal rivers over the last century (Bauer et al. 2015, Madej 2011). In an analysis of gauge data from 21 river gaging stations in an area that covers portions of the Mendocino, Shasta Trinity, Klamath, and Six Rivers National Forests, 10 of the gauges showed an overall decrease in seven-day low flow (Bauer et al. 2015, Madej 2011). Stream gauge data from the Columbia River Basin in the Pacific Northwest showed a 16% decline in spring flow volume, a 5.7 day advancement of spring flow onset, and a 5-38% decline in low flow volume over the last century (Dittmer 2013).

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). Hydrologic extremes, droughts and floods, are predicted to intensify under climate change (IPCC 2014) and these trends are already apparent in the western US (Hayhoe et al. 2004, Kadir et al. 2013). 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). The timing and duration of significant pulses in discharge are particularly important in river ecosystems such as the Eel River Basin of Northern California, where native biota are adapted to Mediterranean seasonality of flows (Kupferberg et al. 2012, Power et al. 2015, in press).

Fire

Data on forest fire frequency, size, and total area burned all show strong increases in California 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. Northern California forests have had substantially increased wildfire activity, with most wildfires occurring in years with early springs (Westerling et al. 2006). This increase is likely attributable to both climate and land-use effects. Large percentage changes in moisture deficits in Northern California forests, according to Westerling et al. (2006), were strongly associated with advances in the timing of spring, but this area also includes substantial forested area where forest densification after fire exclusion, timber harvesting, and mining activities have led to increased forest densities and fire risks (McKelvey et al. 1996, Gruell 2001).

Much of northern California north of the Tehachapi Mountains has missed multiple fire cycles owing to fire suppression, with low- and mid-elevation vegetation types such as oak woodlands, yellow pine, and mixed-conifer forests missing the most fire cycles (Safford and Van de Water 2014). More than 85 percent of Forest Service lands in NW California are burning either less frequently or much less frequently currently than under the pre-Euro-American settlement fire regime, as compared with 67 percent of Forest Service and National Park Service lands in the Sierra Nevada and 19 percent in southern California (Safford and Van de Water 2014).

Miller et al. (2012) found no temporal trend in the annual proportion of fire area burning at high-severity within fires >400 ha occurring on the four National Forests of NW California during the period 1987-2008. However, mean and maximum fire size and total annual area burned all increased over the period from 1910 to 2008 and regional fire rotation fell to 95 years by 2008. During 1987-2008, Miller et al. (2012) found that the percentage of high-severity fire in conifer-dominated forests of smaller average diameter and lower percent cover was generally higher than in forests of larger diameter and higher cover. For areas that burned more than once during this period, severity (a measure of the effect of fire on vegetation) in conifer and hardwood forests was higher the second time burned versus the first time burned, regardless of tree density and size class. Closed forests of medium and large diameter trees that had previously burned between 1921 and 1986 burned at slightly lower severities than similar forests that had last burned before 1921. Miller et al. (2012) also found that years with larger fires and greatest area burned were produced by region-wide lightning events, and characterized by less winter and spring precipitation than in years dominated by smaller human ignited fires, but that the percentage of high-severity fire was generally less in region-wide lightning events.

Vegetation

Mediterranean climate regions like California exhibit high levels of plant richness and endemism and are also among those most sensitive to climate and land-use change (Cowling et al. 1996, Underwood et al. 2009). Where it is able, 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). 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.

Most of the changes in observed in vegetation over the last century can be linked to coupled effects of land-use decisions and climate change. For example, fire suppression has been practiced as a federal policy since 1935. In addition, many forests were harvested using even-aged systems early in the 1900s followed by a diverse group of silvicultural operations (Laudenslayer and Darr 1990). Fire exclusion has resulted in increased tree densities and a reduction in shade intolerant species (Parsons and DeBenedetti 1979; North et al. 2007), although the ecological significance of these changes is more important in drier, historically pine-dominated forests than in moister, fir-dominated forests. Skinner (1995) found that forest openings decreased and distances between openings increased from 1944 to 1985 in portions of the Dillon, Clear, and Swillup Creek watersheds near Happy Camp. Working at Whiskeytown National Recreation Area, Leonzo and Keyes (2010) documented major changes over the last ½ century in the structure and composition of "relict" old-growth ponderosa pine stands, with young individuals of shade tolerant species like Douglas-fir, white fir and tan oak comprising 10 times higher stem densities than the once dominant pine.

Van Mantgem et al. (2009) documented widespread increases in tree mortality in old-growth forests across the west, including northern California. Their plots had not experienced increases in density or basal area during the 15-40 year period between first and last census. The highest mortality rates were documented in the Sierra Nevada, and in middle elevation forests (3300-6700 feet). Higher elevation forests (>6700 feet) showed the lowest mortality rates. Van Mantgem et al. (2009) ascribed the mortality patterns they analyzed to regional climate warming and associated drought stress.

Evidence suggests that old-growth forests can be susceptible to a wide range of stressors, including the disruption of historical disturbance regimes such as fire (Agee 1993), invasive species and pathogens (McDonald and Hoff 2001, Rizzo and Garbelotto 2003), and increasing temperatures (van Mantgem et al. 2009, Allen et al. 2010, Peng et al. 2011, Williams et al. 2012). Recent work by Van Mantgem and Sarr (2015) in diverse old-growth forests across a broad range of climates in the Klamath region further demonstrates the high correlation between forest structure and diversity with climate, as well as the complexity inherent in predicting future forest conditions in this region.

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 already 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).

Indirect climate change impacts on wildlife over the last century have included changes to species habitats, as well as to patterns in disturbances, parasitism, and disease. Halofsky et al. (2011) ranked habitat specialists like the Northern Spotted Owl and American marten, and species like Clark's Nutcracker that inhabit sensitive habitat, as highly vulnerable to climate change. Declines in Marbled Murrelet populations early this century may be partially attributable to loss of nesting habitat to increasing disturbances like fire (Miller et al. 2012). In other areas in the Western US, decreasing songbird diversity and abundance has been indirectly attributed to decreasing snowfall patterns (Martin & Maron 2012). Low rates of snowfall allow for increased over-winter herbivory by ungulates like elk, thus decreasing growth and abundance of some tree species, in turn decreasing associated songbird abundances (Martin 2007; Martin & Maron 2012; Brodie et al. 2012). Increased water temperatures promote populations of parasites like copepods, which negatively affect the fitness of fish and amphibian species (Kupferberg et al. 2009). Species like the protected Foothill Yellow-legged frog (*Rana boylii*) have been shown suffer higher outbreaks of copepod parasites with increased water temperatures and drought induced decreases in water flows in Northern California (Kupferberg et al. 2009).

Another 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 California plant species (Memmott et al. 2007).

III. Future projections

Temperature and Precipitation

As of today, no published climate change or vegetation change modeling has been carried out for the Shasta-Trinity National Forest. 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 (Thrasher et al. 2013), 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 GCMs 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 1º C increase in temperature to an 8% decrease (Gutowski et al. 2000, Hakkarinen and Smith 2003).

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.

GCM projections of precipitation over California tend to disagree on the sign of change (e.g. Das et al. 2013, Neelin et al. 2013, Berg et al. 2015) and projected trends throughout the 21st century are generally insignificant (Berg and Hall 2015). Despite global projections for increases in precipitation extremes (Kharin et al. 2013; Kharin et al. 2007; Sun et al. 2007), Cayan et al. (2008) found only modest increases in the number and magnitude of large precipitation events in California. However, Berg and Hall's (2015) analysis of 34 global climate models projects increases in the frequency of interannual precipitation extremes over California, with extremely dry wet seasons becoming roughly 1.5-2 times more common and wet extremes generally tripling in frequency by the end of the century. The north and south coasts of California are also projected to experience the largest increase in humid nighttime heat wave events (Gershunov and Guirguis 2012).

Hydrology

Although climate models diverge with respect to future trends in precipitation over NW California, there is widespread agreement that the trend toward lower SWE and earlier snowmelt will continue (Leung and Wigmosta, 1999; McCabe and Wolock, 1999; Miller et al. 2003; Snyder et al. 2004; Barnett et al. 2005; Zhu et al. 2005; Vicuna et al. 2007; Van Kirk and Naman 2008). In basins without winter snow accumulation, such as the Eel River basin, base flow is relatively insensitive to increasing temperature (Miller et al. 2003). If precipitation does increase, streamflow volumes during high flow events could greatly increase. 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). Under continued snowpack loss, Knowles and Cayan (2002) project that spring and early summer flows on the upper Sacramento River may decrease by as much as 30% by 2060, and that annual flow volume could drop by 20% by 2090; more snow-dominated river basins may see much greater changes. Because of the relatively low mountain elevations in NW California, stream flow in most rivers is more sensitive to changes in precipitation than changes in temperature, as snowpack input to flow is relatively low (Miller et al. 2003).

A downscaling of three climate models (CSIRO, MIROC, and Hadley) for the Rogue River Basin in southwest Oregon and the Klamath River Basin led to the following general future projections for hydrology in NW California and SW Oregon (Doppelt et al. 2008, Barr et al.

2010): Total precipitation may remain roughly similar to historical levels, but may shift in seasonality to fall predominantly in mid-winter months. Rising temperatures will increase the percentage of precipitation falling as rain and decrease snowpack considerably, particularly at lower elevations. The area is likely to experience more severe storm events, variable weather, higher and flashier winter and spring runoff events, and increased flooding. Both wet and dry cycles are also likely to last longer and be more extreme, leading to periods of deeper drought as well as periods of more extensive flooding.

While hydrological changes in snow-dominated areas like the Sierra Nevada will mainly depend on shifts in precipitation patterns, vegetation shifts may play a more central role in changes to hydrology in lower elevation, shrub-dominated systems (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).

Using the Basin Characterization Model (BCM), a regional water balance model, Thorne et al. (2015) assessed the responses of snowpack, climatic water deficit (CWD), recharge, and runoff to changing climate across 5135 watersheds comprising California. Under both the GFDL and PCM projections, CWD increases by one to two standard deviations in almost all watersheds in northwestern California. Snowpack, runoff, and recharge all continue to decrease and are amplified under future projections throughout northwestern California. Watersheds west of Mount Shasta, where relatively little change has occurred historically, are predicted to experience high levels of change under both future projections.

Increased water demand, extended drought periods, and high precipitation variability are likely to increase ecosystem vulnerability in a changing climate.

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, Westerling and Bryant 2006). In the Pacific Northwest, longer, hotter, and drier fire seasons are projected under future climate change scenarios, and the area burned by wildfires is projected to increase as a result (Wimberly and Liu 2014). 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 4+ times the current levels in Mendocino area shrublands and forestlands by the end of the century (Figure 8).

The MC1 runs reported in Barr et al. (2010) project increases in annual fire area in the Klamath River Basin of 11-22% by 2100, resulting in as many as 330,000 acres (134,000 ha) burned in an average year. Increased frequencies and/or intensities of fire in coniferous forest in California will almost certainly drive changes in tree species composition (Lenihan et al. 2003), and will likely reduce the size and extent of late-successional refugia (USFS and BLM 1994, McKenzie et al. 2004). Thus, if fire becomes more active under future climates, there may be significant repercussions for old growth forest and old growth-dependent flora and fauna.

Fire regimes are driven principally by the effects of weather/climate and fuel type and availability (Agee 1993, Bond and van Wilgen 1996). Eighty years of effective fire suppression in the American West have led to fuel-rich conditions that are conducive to intense forest fires that remove significant amounts of biomass (McKelvey et al. 1996, Arno and Fiedler 2005, Miller et al. 2009), and most future climate modeling predicts climatic conditions that will likely exacerbate these conditions. Basing their analysis on two GCMs under the conditions of doubled atmospheric CO_2 and increased annual precipitation, Flannigan et al. (2000) predicted that mean fire severity in California (measured by difficulty of control) would increase by about 10% averaged across the state. 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 usually assumed to be inversely related (Pickett and White 1985), and a number of researchers have demonstrated this relationship for California 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.

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 grasslands. Thus if conversion of shrublands to grasslands continues as predicted (see vegetation section), we may expect larger, more frequent fires in drier, non-forested portions of the Mendocino National Forest (Minnich and Dezzani 1998).

Climate change may also impose greater constraints on the use of prescribed fire, including both planned ignitions and managed wildfires (Wimberly and Liu 2014). Prescribed burning is a critical component of fuel treatments and landscape restoration in drier forests of the Klamath Mountain region and has proven more effective than thinning alone at reducing the severity of large fires (Agee and Skinner 2005, Raymond and Peterson 2005, Wimberly et al. 2009, Prichard et al. 2010, Prichard and Kennedy 2012). Prescribed burning must be conducted during suitable burn windows, which are highly weather dependent, in order to allow for appropriate fire behavior and effects (Quinn-Davidson and Varner 2012, Ryan et al. 2013). The ecological responses of plants, wildlife, and soils to prescribed burning can vary with the season of burning (Knapp et al. 2009). Changes in climate that extend the length of the fire season could either increase or decrease the time during which there is suitable weather for prescribed burning.

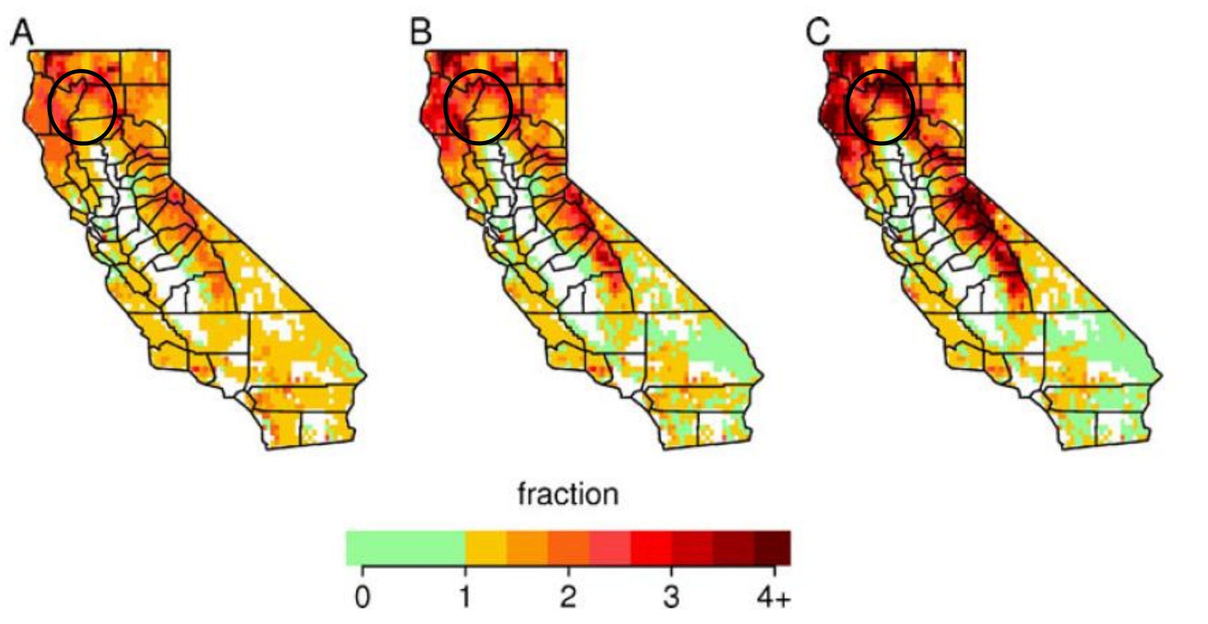


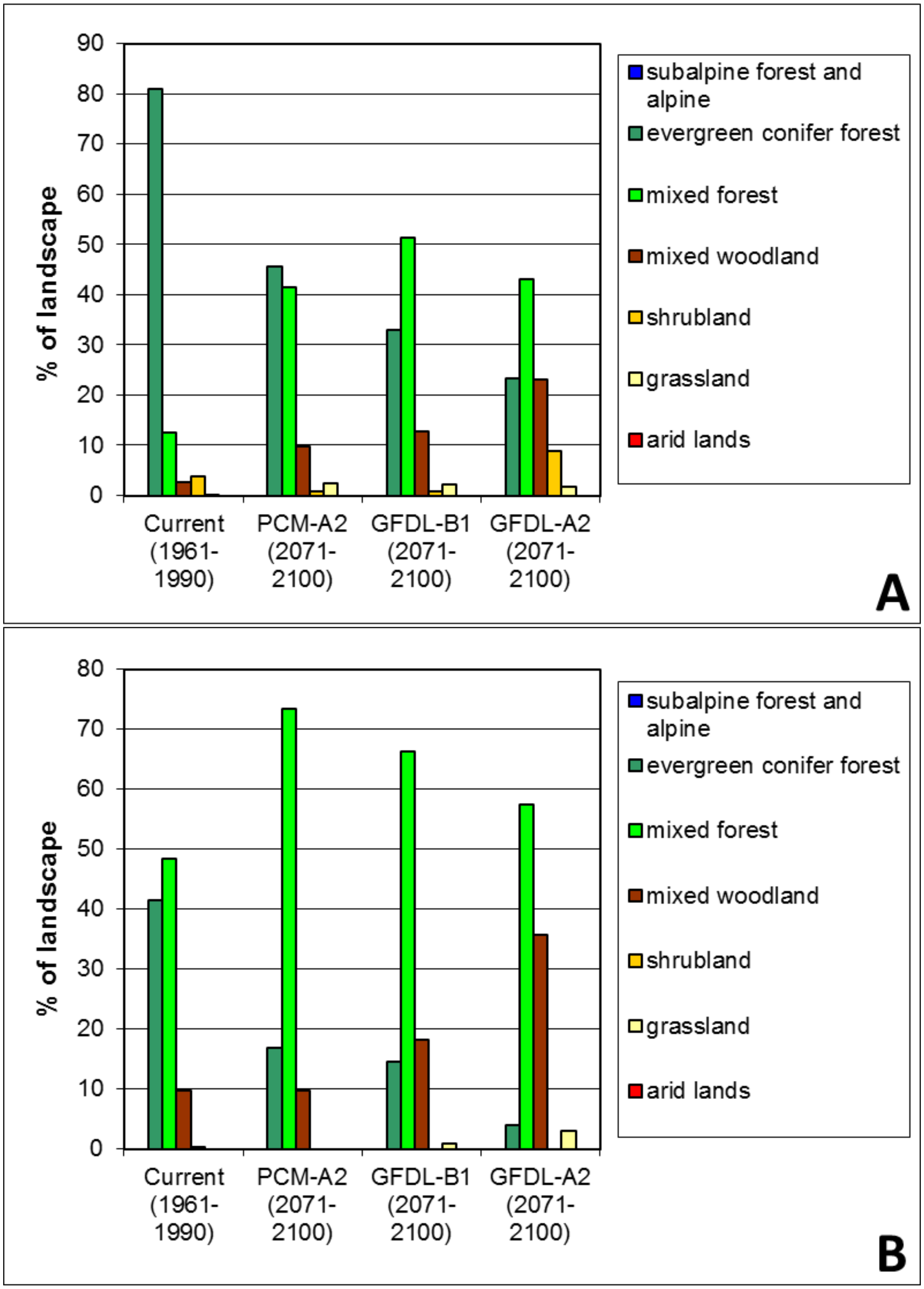
Figure 8. Proportional change in projected mean annual area burned for the 2050-2099 period relative to the mean annual area burned for the reference period (1950-1999) for three climate change scenarios. "1" = unchanged; "2" = 2x the reference condition, etc. A represents the NCAR PCM1 climate scenarios (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). SHF 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 Shasta-Trinity National Forest as a unit. Based on their modeling results, Lenihan et al. (2003, 2008) projected significant declines in conifer-dominated forests and their subsequent replacement by hardwood-dominated forests along the Northern California Coast Range under all future climate scenarios (Figure 9). In the drier Interior Northern California Coast Range, they projected declines in shrubland and oak woodlands and an increase in grassland due to higher fire frequencies; hardwood-dominated forests also increase in area (Figure 9). Hayhoe et al. (2005) also used the MC1 ecosystem model to predict vegetation and ecosystem changes under a number of different future greenhouse gas emissions scenarios. Their results were qualitatively similar to the Lenihan et al. (2003, 2008) results.

Barr et al. (2010) report on a set of MC1 runs under three GCMs for the Klamath River Basin but do not provide quantitative outputs. In general, by 2100 the upper basin (Oregon) is projected to support primarily grassland in place of the sagebrush and juniper ecosystems that currently dominate the area. In the lower basin (California), conditions suitable for hardwood forests (oaks, tan oak, madrone, etc.) are projected to expand while those suitable for conifer-dominated forests are projected to contract.

Loarie et al. (2008) projected that 2/3 of California’s native flora will experience >80% reduction in range size by 2100. Endemic plant species that specialize in uncommon or sparsely distributed habitat (e.g. serpentine 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. Conversely, areas resistant to change, such as north facing slopes or areas with deep, well-watered soils, may provide potential refugia (Olson et al. 2012, van Mantgem and Sarr 2015). Topographic microclimates play an important role in species distributions (Randin et al. 2009, Scherrer and Körner 2011, Lenoir et al. 2013). In the Klamath region, if warming climatic trends are accompanied by drying during the growing season, mesic topographic microclimates are likely to become increasingly important microrefugia (Dobrowski 2010, Copeland and Harrison 2015).



% of landscape
90
80
70
60
50
40
30
20
10
0
subalpine forest and alpine
evergreen conifer forest
mixed forest
mixed woodland
shrubland
grassland
arid lands
Current (1961-1990)
PCM-A2 (2071-2100)
GFDL-B1 (2071-2100)
GFDL-A2 (2071-2100)
A
% of landscape
80
70
60
50
40
30
20
10
0
subalpine forest and alpine
evergreen conifer forest
mixed forest
mixed woodland
shrubland
grassland
arid lands
Current (1961-1990)
PCM-A2 (2071-2100)
GFDL-B1 (2071-2100)
GFDL-A2 (2071-2100)
B

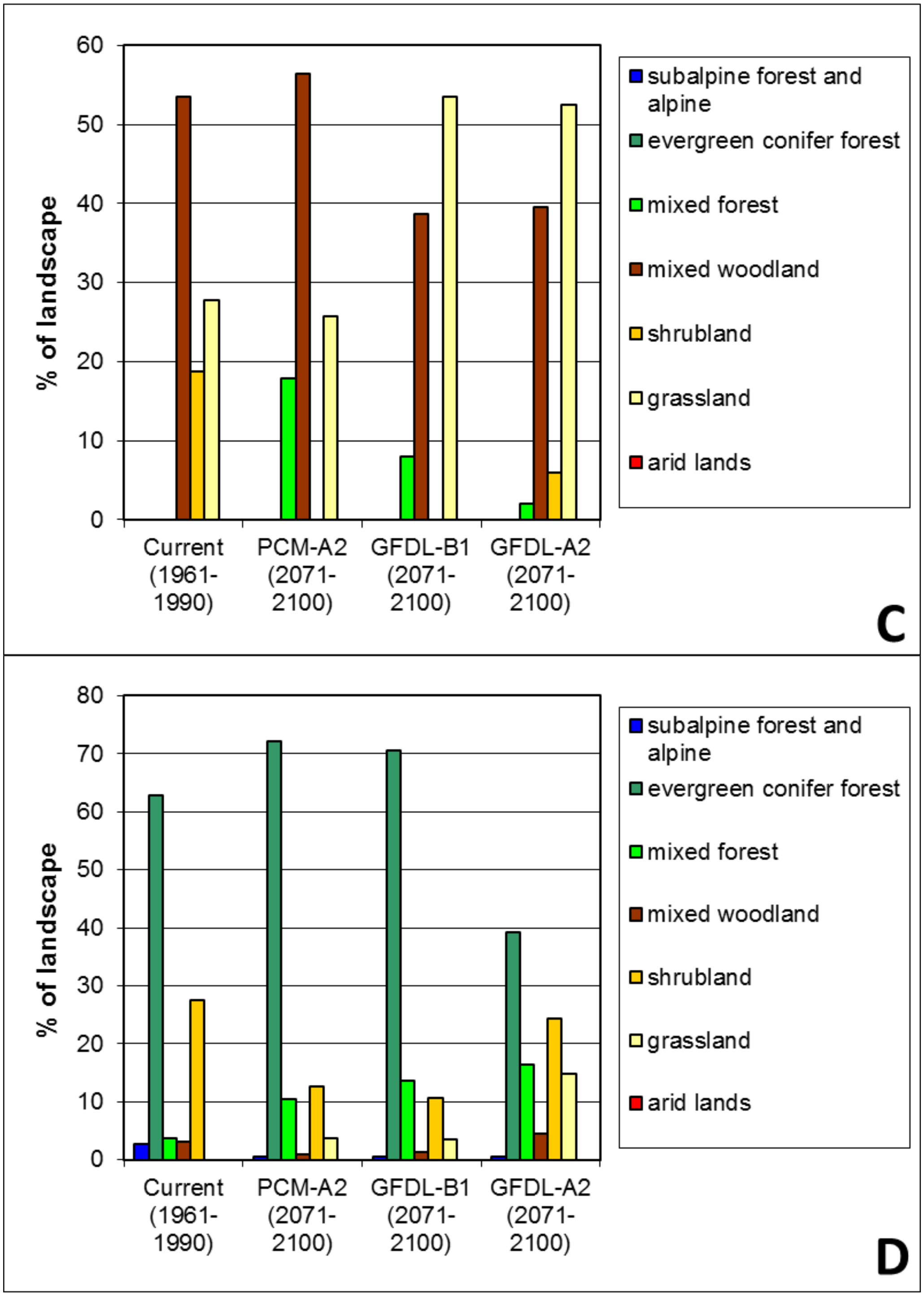


Figure 9. MC1 outputs for the (A) Klamath Mountains, (B) Northern California Coast Ranges, (C) Northern Interior Coast Ranges, and (D) Southern Cascades Ecological Sections, current vs. future projections of vegetation extent. These Ecological Sections include all of the Shasta-Trinity National Forests and some surrounding area. 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). From Lenihan et al. (2008).

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 by the end of this century. 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 Swainson's hawk, Western Grebe, Swainson's Thrush, and Vaux's Swift (Gardali et al. 2012). 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.

Direct and indirect effects will continue to impacts wildlife species in the future, likely at an accelerating pace. Lawler et al (2012) investigated the possible effects of climate change on selected species of the genus Martes and found that macroclimate conditions closely correlated with Pacific fisher (*Martes pennanti*) presence in California were likely to change greatly over the next century, resulting in a possibly pronounced loss of suitable habitat. Their results suggested that martens and fishers will be highly sensitive to climate change. A more recent analysis of climate impacts on fisher and marten habitat in the Sierra Nevada found that predicted marten distribution shifted to higher elevations, became more fragmented, and decreased in area by 40−85% (depending on GCM scenario; Spencer et al. 2015). On the other hand, predicted changes in fisher distribution were highly variable and inconsistent, showing some increases and some decreases in extent, suggesting high uncertainty in climate change effects on fishers (Spencer et al. 2015). Population growth in Northern Spotted Owls is positively associated with wet, cool summer conditions, likely an effect of prey availability, but climate models predict warmer, drier summers which will likely negatively impact spotted owl populations (Glenn et al. 2010).

Those aquatic species with a competitive advantage in colder waters will also likely suffer losses due to both thermal stress and increased competition as water temperatures rise (Rahel et al. 2008; Kennedy et al. 2009). Salmonids may be particularly sensitive to warming water temperatures (ISAB 2007). Power et al. (2015) suggested that two likely future scenarios (drier winters followed by drier summers; or wetter winters followed by drier summers) may trigger cyanobacteria blooms, harmful to salmonids and other fish. According to Power et al. (2005), "If dry winters are followed by dry summers, salmonids will be heat-stressed as well as hungry. The worst case appears to be if scouring winter flows release algal blooms, but abrupt decreases in summer baseflows cause these to rot in the channel as pools warm and stagnate." 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). Increased summer temperatures, and resulting declines in growth and productivity, are likely to further stress steelhead and rainbow trout populations like those in the low-order streams in the South Fork Trinity River basin (McCarthy et al. 2009). O'Neal

(2002) suggested that by 2090, 25 to 41% of currently suitable California streams may be too warm to support trout.

Changing disturbance regimes associated with climate change will also continue to impact wildlife species in complex ways in the future. Species that require older, denser, and more structurally complex forest conditions, like Pacific Fisher and the Northern Spotted Owl, will likely be negatively impacted by changes in fire regimes associated with climate change (Scheller et al. 2011). Lawler et al. (2012) noted that fisher habitat is driven to a great extent by local vegetation features and the authors examined stand-level implications of fire under a series of future fire scenarios, since fire occurrence and behavior, largely driven by climate/weather, have substantial effects on local vegetation. They recommended protecting fisher habitat through targeted forest-fuel treatment, and applying more liberal fire-management policies to naturally ignited fires during moderate weather conditions. Sensitive benthic invertebrate populations may also be reduced by increases in large and severe wildfires that are likely to be associated with climate warming (Oliver et al. 2012). Larger effects will likely be observed in small, first-order streams (Oliver et al. 2012).

As the loss of synchrony between reproductive or migratory phenology and resource availability becomes more pronounced, for species like bats that have specialized diets and carefully balanced energy budgets (e.g. Pallid and Townsend's big-eared bats on the Mendocino), a shift in the timing of invertebrate prey availability could result in reduced survival or fecundity (Halofsky et al. 2011).

Loarie et al. (2008) identified the coastal mountains of Northwest California as an important climate change refugium, defined as an area projected to sustain species with otherwise shrinking ranges. Authors like Loarie et al. and Lawler et al. recommend novel adaptive management approaches and large-scale planning efforts that promote landscape/regional habitat connectivity. Loarie et al. (2008) also recommended consideration of human-assisted dispersal of California's flora and prioritization of climate change refugia for conservation and restoration.

Literature Cited

Agee. J. K. 1993. Fire ecology of Pacific Northwest forests. Washington, DC: Island Press.

Agee, J. K., and C. N. Skinner. 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management 221:83-96.

Allen, C. D., A. K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T. Kitzberger, A. Rigling, D. D. Breshears, E. H. Hogg, P. Gonzalez, R. Fensham, Z. Zhang, J. Castro, N. Demidova, J. H. Lim, G Allard, S. W. Running, A Semerci, and N. Cobb. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecology and Management 259:660-684.

Arno, S. F., and C. E. Fiedler. 2005. Mimicking nature's fire. Restoring fire-prone forests in the West. Island Press, Washington, DC, USA.

Bakun, A. 1990. Global climate change and intensification of coastal ocean upwelling. Science 247:198-201.

Barnett, T. P., D. W. Pierce, H. G. Hidalgo, C. Bonfils, B. D. Santer, T. Das, G. Bala, A. W. Wood, T. Nozawa, A. A. Mirin, D. R. Cayan, and M. D. Dettinger. 2008. Human-induced changes in the hydrology of the western United States. Science 319 (5866): 1080-1083.

Barr, B. R, M.E. Koopman, C. D. Williams, S. J.Vynne, R. Hamilton, and B. Doppelt. 2010. Preparing for climate change in the Klamath Basin. University of Oregon Climate Leadership Initiative and National Center for Conservation Science and Policy. Report

Bauer, S., J. Olson, A. Cockrill, M. van Hattem, L. Miller, M. Tauzer, and G. Leppig. 2015. Impacts of surface water diversions for marijuana cultivation on aquatic habitat in four northwestern California watersheds. PLoS ONE 10(3): e0120016. doi:10.1371/journal.pone.0120016.

Berg, N. and A. Hall. 2015. Increased interannual precipitation extremes over California under climate change. Journal of Climate 28:6324-6334.

Berg, N. A. Hall, F. Sun, S. Capps, D. Walton, B. Langenbrunner, and J. D. Neelin. 2015. Twenty-first century precipitation changes over the Los Angeles region. Journal of Climate 28:401-421.

Bond, W. J., and B. W. van Wilgen. 1996. Fire and plants. Chapman and Hall, London, England.

Brodie, J., E. Post, F. Watson, and J. Berge. 2012. Climate change intensification of herbivore impacts on tree recruitment. Proceedings of the Royal Society 279:1366 – 1370.

Cayan, D. R., E. P. Maurer, M. D. Dettinger, M. Tyree, and K. Hayhoe. 2008. Climate change scenarios for the California region. Climate Change 87 (Suppl 1):S21-S42.

Conlisk, E., A. D. Syphard, J. Franklin, L. Flint, A. Flint, and H. Regan. 2013. Uncertainty in assessing the impacts of global change with coupled dynamic species distribution and population models. Global Change Biology 19:858 – 869.

Copeland, S. M., and S. P. Harrison. 2015. Identifying plant traits associated with topographic contrasts in a rugged and diverse region (Klamath-Siskiyou Mts, OR, USA). Ecography 38:569-577.

Cordero, E. C., W. Kessomkiat, J. Abatzoglou, and S. A. Mauget. 2011. The identification of distinct patterns in California temperature trends. Climatic Change 108:357-382.

Cowling, R. M., F. Ojeda, B. B. Lamont, P. W. Rundel, and R. Lechmere-Oertel. 2005. Rainfall reliability, a neglected factor in explaining convergence and divergence of plant traits in fire-prone Mediterranean-climate ecosystems. Global Ecology and Biogeography 14:509-519.

Dale, V. H., L. A. Joyce, S. McNulty, R. P. Neilson, M. P. Ayres, M. D. Flannigan, P. J. Hanson, L. C. Irland, A. E. Lugo, C. J. Peterson, D. Simberloff, F. J. Swanson, B. J. Stocks, and B. M. Wotton. 2001. Climate change and forest disturbances. BioScience 51: 723-734.

Daly, C., R. P. Neilson, and D. L. Phillips. 1994. A statistical-topographic model for mapping climatological precipitation over mountainous terrain. Journal of Applied Meteorology 33:140–158.

Das, T., E. P. Maurer, D. W. Pierce, M. D. Dettinger, and D. R. Cayan. 2013. Increases in flood magnitudes in California under warming climates. Journal of Hydrology 501:101-110.

Davis, F. W., and J. Michaelsen. 1995. Sensitivity of fire regime in chaparral ecosystems to climate change, in Global Change and Mediterranean Type Ecosystems, edited by J. M. Moreno and W. C. Oechel, p. 435 –456, Springer-Verlag, New York.

Dettinger, M. D., F. M. Ralph, T. Das, P. J. Neiman, P. J., and D. R. Cayan. 2011. Atmospheric rivers, floods and the water resources of California. Water 3 (2):445-478.

Dettinger, M. D. 2005. From climate-change spaghetti to climate-change distributions for 21st century California. San Francisco Estuary and Watershed Science Vol. 3, Issue 1, (March 2005), Article 4. http://repositories.cdlib.org/jmie/sfews/vol3/iss1/art4

Diffenbaugh, N. S., D. L. Swain, and D. Touma. 2015. Anthropogenic warming has increased drought risk in California. Proceedings of the National Academy of Sciences 112:3931-3936.

Dittmer, K. 2013. Changing streamflow on Columbia basin tribal lands-climate change and salmon. Climate Change 120:627-641.

Dobrowski, S. Z. 2010. A climate basis for microrefugia: the influence of terrain on climate. Global Change Biology 17:1022-1035.

Doppelt, B., R. Hamilton, C. D. Williams, and M. Koopman. 2008. Preparing for climate change in the Rogue River Basin of Southwest Oregon: stressors, risks, and recommendations for increasing resilience and resistance in human, built, economic, and natural systems. GEOS Institute. Dec. 2008. http://www.geosinstitute.org/white-papers-publications/climate-change.html.

Dunn, P. O., and D. W. Winkler. 1999. Climate change has affected the breeding date of tree swallows throughout North America. Proceedings of the Royal Society of London 266:2487-2490.

Flannigan M. D., B. J. Stocks, and B. M. Wotton. 2000. Climate change and forest fires. Science of the Total Environment 262: 221–229.

Forister, M. L., A. C. McCall, N. J. Sanders, J. A. Fordyce, J. H. Thorne, J. O'Brien, D. P. Waetjen, and A. M. Shapiro. 2010. Compounded effects of climate change and habitat alteration shift patterns of butterfly diversity. Proceedings of the National Academy of Sciences 107:2088-2092.

Gabet, E. J. and T. Dunne. 2003. A stochastic sediment delivery model for a steep Mediterranean landscape. Water Resources Research 39:1237 – 1248.

Gershunov, A., and K. Guirguis. 2012. California heat waves in the present and future. Geophysical Research Letters 39.

Glenn, E. M., R. G. Anthony, and E. D. Forsman. 2010. Population trends in northern spotted owls: Associations with climate in the Pacific Northwest. Biological Conservation 143:2543-2552. DOI: 10.1016/j.biocon.2010.06.021

Griffin, D., and K. J. Anchukaitis. 2014. How unusual is the 2012–2014 California drought? Geophysical Research Letters 41:9017-9023.

Gruel, G. E. 2001. Fire in Sierra Nevada Forests: A Photographic interpretation of ecological change since 1849. Mountain Press: Missoula, MT.

Grundstein, A., and T. L. Mote. 2010. Trends in average snow depth across the western United states. Physical Geography 31 (2):172-185.

Gutowski, W. J., Z. Pan, C. J. Anderson, R. W. Arritt, F. Otieno, E. S. Takle, J. H. Christensen, and O. B. Christensen. 2000. What RCM data are available for California impacts modeling? California Energy Commission Workshop on Climate Change Scenarios for California, 12-13 June, 2000. California Energy Commission, Sacramento, CA, USA.

Guyette, R. P., M. C. Stambaugh, D. C. Dey, and R. M. Muzika. 2012. Predicting Fire Frequency with Chemistry and Climate. Ecosystems 15:322-335.

Hakkarinen, C., and J. Smith. 2003. Appendix I. Climate scenarios for a California Energy Commission study of the potential effects of climate change on California: summary of a June

12-13, 2000, workshop. *In* Global Climate Change and California: Potential Implications for Ecosystems, Health, and the Economy. EPRI (Electric Power Research Institute), Palo Alto, CA, USA. 38 pp.

Halofsky, J. E., Peterson, D. L., O'Halloran, K. A. & Hawkins Hoffman, C., eds. 2011. Adapting to climate change at Olympic National Forest and Olympic National Park. General Technical Report PNW-GTR-844. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 130p.

Hamlet, A. F., P. W. Mote, M. P. Clark, and D. P. Lettenmaier. 2007. Twentieth-century trends in runoff, evapotranspiration, and soil moisture in the western United States. Journal of Climate 20:1468-1486.

Hamlet, A. F., P. W. Mote, M. P. Clark, and D. P. Lettenmaier. 2005. Effects of temperature and precipitation variability on snowpack trends in the western United States. Journal of Climate 18:4545-4561.

Hayhoe, K., et al. (18 co-authors). 2004. Emissions pathways, climate change, and impacts on California. Proceedings of the National Academy of Sciences 101:12422-12427.

IPCC. 2014. Climate Change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of working group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Matrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, and L. L. White (eds.). Cambridge University Press, Cambridge, UK and New York.

ISAB - Independent Scientific Advisory Board. 2007. Climate change impacts on Columbia River Basin fish and wildlife. ISAB Climate Change Report ISAB 2007-2. Portland, OR.

Jiguet, F., R. Julliard, C. D. Thomas, O. Dehorter, S. E. Newson, and D. Couvet. 2006. Thermal range predicts bird population resilience to extreme high temperatures. Ecology Letters 9:1321-1330.

Kadir, T., L. Mazur, C. Milanes, and K. Randles (eds.). 2013. Indicators of climate change in California. Office of Environmental Health Hazard Assessment, California Environmental Protection Agency, Sacramento, California.

Kaushal, S. S., G. E. Likens, N. A. Jaworski, M. L. Pace, A. M. Sides, D. Seekell, K. T. Belt, D. H. Secor, and R. L. Wingate. 2010. Rising stream and river temperatures in the United States. Frontiers in Ecology and the Environment 8:461-466.

Kennedy, T. L., D. S. Gutzler, and R. L. Leung. 2009. Predicting future threats to the long-term survival of Gila trout using a high-resolution simulation of climate change. Climate Change 94: 503-515.

Kharin, V. V., F. Zwiers, X. Zhang, and M. Wehner. 2013. Changes in temperature and precipitation extremes in the CMIP5 ensemble. Climatic Change 119:345-357.

Kharin, V. V., F. W. Zwiers, X. Zhang, and G. C. Hegerl. 2007. Changes in temperature and precipitation extremes in the IPCC ensemble of global coupled model simulations. Journal of Climate 20:1419-1444.

Knapp, E. E., B. L. Estes, and C. N. Skinner. 2009 Ecological effects of prescribed fire season: a literature review and synthesis for managers. General Technical Report PSW-GTR-224. USDA Forest Service, Pacific Southwest Research Station, Albany, CA.

Knowles, N., M. D. Dettinger, and D. R. Cayan. 2006. Trends in snowfall versus rainfall in the western United States. Journal of Climate 19:4545-4559.

Knowles, N. and D. R. Cayan 2004. Elevational dependence of projected hydrologic changes in the San Francisco estuary and watershed. Climatic Change 62:319-336.

Knowles, N., and D. R. Cayan. 2002. Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary. Geophysical Research Letters 29:1891-1895.

Kupferberg, S. J., W. J. Palen, A. J. Lind, S. Bobzien, A. Catenazzi, J. Drennan, and M. E. Power. 2012. Effects of flow regimes altered by dams on survival, population decilmates, and range-wide losses of California river-breeding frogs. Conservation Biology 26:513-524.

Kupferberg, S. J., A. Catenazzi, K. Lunde, A. J. Lind, and W. J. Palen. 2009. Parasitic Copepod (Lernaea cyprinacea) outbreaks in Foohill Yellow-legged Frogs (Rana boylii) linked to unusually warm summers and amphibian malformations in Northern California. Copeia 3:529-537.

LaDochy, S., R. Medina, and W. Patzert. 2007. Recent California climate variability: spatial and temporal patterns in temperature trends. Climate Research 33:159-169.

Laudenslayer, W. F., and H. H. Darr. 1990. Historical effects of logging on forests of the Cascade and Sierra Nevada ranges of California. Trans. West. Sect. Wildlife Society 26:12-23.

Lawler, J. J., H. D. Safford, and E. H. Girvetz. 2012. Martens and fishers in a changing climate. in K. B. Aubry, W. J. Zielinski, M. G. Raphael, G. Proulx, and S. W. Buskirk (eds). Biology and Conservation of Martens, Sables, and Fishers: a New Synthesis. Cornell University Press, Ithaca, NY.

Lawler, J. J., S. L. Shafer, B. A. Bancroft, and A. R. Blaustein. 2009a. Projected climate impacts for the amphibians of the western hemisphere. Conservation Biology 24: 38-50.

Lawler, J. J., S. L. Shafer, D. White, P. Kareiva, E. P. Maurer, A. R. Blaustein, and P. J. Bartlein. 2009b. Projected climate-induced faunal change in the western hemisphere. Ecology 90:588-597.

Lenihan, J. M., R. Drapek, D. Bachelet and R. P. Neilson. 2003. Climate change effects on vegetation distribution, carbon, and fire in California. Ecological Applications 13:1667-1681.

Lenihan, J. M., D. Bachelet, R. P. Neilson, and R. Drapek. 2008. Response of vegetation distribution, ecosystem productivity, and fire to climate change scenarios for California. Climate Change 87 (Suppl 1):S215-S230.

Lenoir, J. et al. 2013. Local temperatures inferred from plant communities suggest strong spatial buffering of climate warming across northern Europe. Global Change Biology 19:1470-1481.

Leonzo, C. M, and C. R. Keyes. 2010. Fire-excluded relict forests in the southeastern Klamath Mountains, California, USA. Fire Ecology 6:62-76.

Leung, L. R. and M. S. Wigmosta. 1999. Potential climate change impacts on mountain watersheds in the Pacific Northwest. Journal of the American Water Resources Association 35:1463-1471.

Loarie, S. R., B. E. Carter, K. Hayhoe, S. McMahon, R. Moe, C. A. Knight, and D. D. Ackerly. 2008. Climate change and the future of California's endemic flora. PLoS ONE 3: e2502.

MacMyonowski, D. P., and T. L. Root. 2007. Climate Change and The Timing of Songbird Migration in California: Focus on Coastal Central and Northern Regions. A report prepared for the California Energy Commission. California Climate Change Center Report Series Number 2007-003.

Madej, M. A. 2011. Analysis of trends in climate, streamflow, and stream temperature in North Coastal California. Proceedings of the Fourth Interagency Conference on Research in the Watersheds. United States Geological Survey.

Mann, M. E., and P. H. Gleick, 2015, Climate change and California drought in the 21st century: Proceedings of the National Academy of Sciences, v. 112, p. 3858-3859.

Martin, T. E. 2007. Climate correlates of 20 years of trophic changes in a high elevation riparian system. Ecology 88:367-380.

Martin, T. E., and J. L. Maron. 2012. Climate impacts on bird and plant communities from altered animal-plant interactions. Nature Climate Change – advance online publication. Doi: 10.1038/NCLIMATE1348.

Maurer, E. P., I. T. Stewart, C. Bonfils, P. B. Duffy, and D. Cayan. 2007. Detection, attribution, and sensitivity of trends toward earlier streamflow in the Sierra Nevada. Journal of Geophysical Research-Atmospheres 112.

McCabe, G. J., and D. M. Wolock. 1999. General-circulation-model simulations of future snowpack in the Western United States. Journal of the American Water Resources Association 35:1473-1484.

McCarthy , S. G., J. J. Duda , J. M. Emlen, G. R. Hodgson, and D. A. Beauchamp. 2009. Linking Habitat Quality with Trophic Performance of Steelhead along Forest Gradients in the South Fork

Trinity River Watershed, California. Transactions of the American Fisheries Society 138:506-521, DOI: 10.1577/T08-053.1.

McDonald, G. I., and R. J. Hoff. 2001. Blister rust: an introduced plague. In D. F. Tomback, S. F. Arno, and R. E. Keane (eds.). Whitebark Pine Communities. Island Press, Washington D.C. Pp. 193-220.

McKelvey, K. S., C. N. Skinner, C. Chang, D. C. Erman, S. J. Husari, D. J. Parsons, J. W. van Wagtendonk, J. W., and C. W. Weatherspoon. 1996. An overview of fire in the Sierra Nevada. *In* Sierra Nevada Ecosystem Project: final report to Congress. Vol. II, Assessments and scientific basis for management options. University of California, Centers for Water and Wildland Resources, Davis, CA, USA. Pp. 1033-1040.

McKenzie, D., Z. Gedalof, D. L. Peterson and P. Mote. 2004. Climatic change, wildfire, and conservation. Conservation Biology 18:890-902.

Memmott, J., P. G. Craze, N. M. Waser, and M. V. Price. 2007. Global warming and the disruption of plant-pollinator interactions. Ecology Letters 10:710-717.

Miller, C., and D. Urban. 1999. Forest pattern, fire and climatic change in the Sierra Nevada. Ecosystems 2:76-87.

Miller, J. D., C. N. Skinner, H. D. Safford, E. E. Knapp, and C. M. Ramirez. 2012. Trends and causes of severity, size, and number of fires in northwestern California, USA. Ecological Applications. 22:184-203.

Miller, J. D., H. D. Safford, M. Crimmins, and A. E. Thode. 2009. Quantitative evidence for increasing forest fire severity in the Sierra Nevada and southern Cascade Mountains, California and Nevada, USA. Ecosystems 12:16-32.

Miller, N. L., K. E. Bashford, and E. Strem. 2003. Potential impacts of climate change on California hydrology. Journal of the American Water Resources Association 39:771-784.

Miller, S. l., M. G. Raphael, G. A. Falxa, C. Strong, J. Baldwin, T. Bloxton, B. M. Galleher, M. Lance, D. Lynch, S. F. Pearson, C. J. Ralph, and R. D. Young. 2012. Recent Population Decline of the Marbled Murrelet in the Pacific Northwest. The Condor 114:771-781.

Minnich, R. A., and R. J. Dezzani. 1998. Historical decline of coastal sage scrub in the Riverside Perris Plain, California. Western Birds 29:366 – 391.

Moritz, C., J. L. Patton, C. J. Conroy, J. L. Parra, G. C. White, and S. R. Beissinger. 2008. Impact of a century of climate change of small-mammal communities in Yosemite National Park, USA. Science 322:261-264.

Moser, S., G. Franco, S. Pittiglio, W. Chou, D. Cayan. 2009. The future is now: An update on climate change science impacts and response options for California. California Climate Change Center Report CEC-500-2008-071, May 2009. California Energy Commission, Sacramento, CA.

Mote, P. W. 2006. Climate-driven variability and trends in mountain snowpack in Western North America. Journal of Climate 19:6209-6220.

Mote, P. W., A. F. Hamlet, M. P. Clark, and D. P. Lettenmaier. 2005. Declining snowpack in Western North America. Bulletin of the American Meteorological Society 86:39-49, doi: 10.1175/BAMS-86-1-39.

Mote, P. W. 2003. Trends in snow water equivalent in the Pacific Northwest and their climatic causes. Geophysical Research Letters 30 (12).

Neelin, J. D., B. Langenbrunner, J. E. Meyerson, A. Hall, and N. Berg. 2013. California winter precipitation change under global warming in the Coupled Model Intercomparion Project Phase 5 Ensemble. Journal of Climate 26:6238-6256.

North, M., J. Innes, and H. Zald. 2007 Comparison of thinning and prescribed fire restoration treatments to Sierran mixed-conifer historic conditions. Canadian Journal of Forest Research 37: 331-42.

Oliver, A. A., M. T. Bogan, D. B. Herbst, and R. A. Dahlgren. 2012. Short-term changes in-stream macroinvertebrate communities following a severe fire in the Lake Tahoe basin, California. Hydrobiologia- advance online publication. DOI 10.1007/s10750-012-1136-7.

Olson, D., D. A. DellaSala, R. F. Noss, J. R. Strittholt, J. Kass, M. E. Koopman, and T. F. Allnutt. 2012. Climate change refugia for biodiversity in the Klamath-Siskiyou ecoregion. Natural Areas Journal 32:65-74.

O'Neal K. Effects of Global Warming on Trout and Salmon in U.S. Streams. 2002. The Natural Resources Defense Council. Available at: Report

Pagano, T. and D. Garen. 2005. A recent increase in western US streamflow variability and persistence. Journal of Hydrometeorology 6:173-179.

Parsons, D. J., and S. H. DeBenedetti. 1979. Impact of fire suppression on a mixed-conifer forest. Forest Ecology and Management 2:21-33.

Pausas, J.G. 2004. Changes in fire and climate in the Eatern Iberian Peninsula (Medterranean Basin). Climate Change 63:337-350.

Peng, C., Z. Ma, X. Lei, Q. Zhu, H. Chen, W. Wang, S. Liu, W. Li, X. Fang, and X. Zhou. 2011. A drought-induced pervasive increase in tree mortality across Canada's boreal forests. Nature Climate Change 1:467-471.

Penuelas, J., P. Prieto, C. Beier, C. Cesaraccio, P. de Angelis, G. de Dato, B. Emmett, M. Estiarte, J. Garadnai, A. Gorissen, E. Lang, G. Kroel-Dulay, L. Llorens, G. Pellizzaro, T. Riis-Nielsen, I. Schmidt, C. Sirca, A. Sowerby, D. Spano, and A. Tietema. 2007. Response of plant species richness and primary productivity in shrublands along a north-south gradient in Europe to seven years of experimental warming and drought: reductions in primary productivity in the heat and drought year of 2003. Global Change Biology 13:2563-2581.

Pickett, S. T. A., and P. S. White. 1985. The Ecology of Natural Disturbance and Patch Dynamics. Academic Press, New York, NY, USA

Power, M. E., S. J. Kupferberg, S. D. Cooper, and M. L. Deas. In press. California's river ecosystems. In: Ecosystems of California. H. Mooney and E. Zavaleta (eds.). University of California Press, Berkeley.

Power, M. E., K. Bouma-Gregson, P. Higgins, and S. M. Carlson. 2015. The Thirsty Eel: Summer and Winter Flow Thresholds that Tilt the Eel River of Northwestern California from Salmon-Supporting to Cyanobacterially Degraded States. Copeia, 2015:200-211. DOI: http://dx.doi.org/10.1643/CE-14-086.

Price, C., and D. Rind. 1994. The impact of a 2 x CO_2 climate on lightning-caused fires. Journal of Climate 7:1484-1494.

Prichard, S. J., and M. C. Kennedy. 2012. Fuel treatment effects on tree mortality following wildfire in dry mixed conifer forests, Washington State, USA. International Journal of Wildland Fire 21:1004-1013.

Prichard, S. J., D. L. Peterson, and K. Jacobson. 2010 Fuel treatments reduce the severity of wildfire effects in dry mixed conifer forest, Washington, USA. Canadian Journal of Forest Research 40:1615-1626.

PRISM. 2015. PRISM climate group website. Available online at: PRISM website

Quinn-Davidson, L. N., and J. M. Varner. 2012. Impediments to prescribed fire across agency, landscape, and manager: an example from northern California. International Journal of Wildland Fire 21:210-218.

Rahel, F. J., B. Bierwagen, and Y. Taniguchi. 2008. Managing aquatic species of conservation concern in the face of climate change and invasive species. Conservation Biology 22:551-561.

Randin, C. F. et al. 2009. Climate change and plant distribution: local models predict high-elevation persistence. Global Change Biology 15:1557-1569.

Rapacciuolo, G., S. P. Maher, A. C. Schneider, T. T. Hammond, M. D. Jabis, R. E. Walsh, K. J. Iknayan, G. K. Walden, M. F. Oldfather, and D. D. Ackerly. 2014. Beyond a warming fingerprint: individualistic biogeographic responses to heterogeneous climate change in California. Global Change Biology 20:2841-2855.

Raymond, C. L., and D. L. Peterson. 2005. Fuel treatments alter the effects of wildfire in a mixed-evergreen forest, Oregon USA. Canadian Journal of Forestry 35:2981-2995.

Reba, M. L., D. Marks, A. Winstral, T. E. Link, and M. Kumar. 2011. Sensitivity of the snowcover energetics in a mountain basin to variations in climate. Hydrological Processes 25:3312-3321.

Regonda, S. K. B. Rajagoplan, M. Clark, and J. Pitlick. 2005. Seasonal shifts in hydroclimatology over the Western United States. Journal of Climate 18:372-384.

Rizzo, D. M., and M. Garbelotto. 2003. Sudden oak death: endangering California and Oregon forest ecosystems. Frontiers in Ecology and the Environment 1:197-204.

Rubidge, E. M., W. B. Monahan, J. L. Parra, S. E. Cameron, and J. S. Brashares. 2011. The role of climate, habitat, and species co-occurrence as drivers of change in small mammal distributions over the past century. Global Change Biology 17: 696-708.

Ryan, K. C., E. E. Knapp, and J. M. Varner. 2013. Prescribed fire in Northern American forests and woodlands: history, current practice, and challenges. Frontiers in Ecology and the Environment 11:e15-e24.

Safford, H. D., and K. M. Van de Water. 2014. Using fire return interval departure (FRID) analysis to map spatial and temporal changes in fire frequency on National Forest lands in California. Research Paper PSW-RP-266. USDA Forest Service, Pacific Southwest Research Station, Albany, California.

Scheller, R. M., W. D. Spencer, H. Rustigian-Romsos, A. D. Syphard, B. C. Ward, and J. R.

Strittholt. 2011. Using stochastic simulation to evaluate competing risks of wildfires and fuels management on an isolated forest carnivore. Landscape Ecology 26: 1491 – 1504.

Scherrer, D. and C. Körner. 2011. Topographically controlled thermal-habitat differentiation buffers alpine plant diversity against climate warming. Journal of Biogeography 38:406-416.

Seavy, N. E., T. Gardali, G. H. Golet, F. T. Griggs, C. A. Howell, R. Kelsey, S. L. Small, J. H. Viers, and J. F. Weigand. 2009. Why climate change makes riparian restoration more important than ever: recommendations for practice and research. Ecological Restoration 27: 330 – 337.

Shuford, W. D. and T. Gardali (eds). 2008. California Bird Species of Special Concern: A ranked assessment of species, subspecies, and distinct populations of birds of immediate conservation concern in California. Western Field Ornithologists and California Department of Fish and Game, California.

Skinner, C. N. 1995. Change in spatial characteristics of forest openings in the Klamath Mountains of northwestern California, USA. Landscape Ecology 10:219-228.

Snyder, M. A., L. C. Sloan, and J. L. Bell. 2004. Modeled regional climate change in the hydrologic regions of California: a CO_2 sensitivity study. Journal of the American Water Resources Association 40:591-601.

Snyder, M. A., L. C. Sloan, N. S. Diffenbaugh, and J. L. Bell. 2003. Future climate change and upwelling in the California Current. Geophysical Research Letters 30:1823-1825.

Spencer, W. D., H. Rustigian-Romsos, K. Ferschweiler, and D. Bachelet. 2015. Simulating Effects of Climate and Vegetation Change on Distributions of Martens and Fishers in the Sierra Nevada, California, Using Maxent and MC1. In: Global Vegetation Dynamics: Concepts and Applications in the MC1 Model (eds D. Bachelet and D. Turner), John Wiley & Sons, Inc, Hoboken, NJ. doi: 10.1002/9781119011705.ch9.

Spracklen, D. V., L. J. Mickley, J. A. Logan, R. C. Hudman, R. Yevich, M. D. Flannigan, and A. L. Westerling. 2009. Impacts of climate change from 2000 to 2050 on wildfire activity and carbonaceous aerosol concentrations in the western United States. Journal of Geophysical Research-Atmospheres 114.

Stewart, I. T., D. R. Cayan, and M. D. Dettinger. 2005. Changes toward earlier streamflow timing across Western North America. Journal of Climate 18:1136-1155.

Stralberg, D., D. Jongsomjit, C. A. Howell, M. A. Snyder, J. D. Alexander, J. A. Wiens, and T. L. Root. 2009. Re-shuffling of species with climate disruption: a no-analog future for California birds? PLoS ONE 4(9): e6825.

Sun, Y., S. Solomon, A. Dai, and R. W. Portmann. 2007. How often will it rain? Journal of Climate 20:4801-4818.

Swetnam, T. W. 1993. Fire history and climate change in giant sequoia groves. Science 262: 885–889.

Tague, C., L. Seaby, and A. Hope. 2009. Modeling the eco-hydrologic response of a Mediterranean type ecosystem to the combined impacts of projected climate change and altered fire frequencies. Climate Change 93:137-155.

Thrasher, B., J. Xiong, W. Wang, F. Melton, A. Michaelis, and R. Nemani. 2013. Downscaled climate projections suitable for resource management. Eos, Transactions American Geophysical Union 94:321-323.

Thorne, J. H., R. M. Boynton, L. E. Flint, and A. L. Flint. 2015. The magnitude and spatial patterns of historical and future hydrologic change in California's watersheds. Ecosphere 6(2):24.

Tingley, M. W., W. B. Monahan, S. R. Beissinger, and C. Moritz. 2009. Birds track their Grinnellian niche through a century of climate change. Proceedings of the National Academy of Sciences 106:19367-19643.

Underwood, E. C., J. H. Viers, K. R. Klausmeyer, R. L. Cox, and M. R. Shaw. 2009. Threats and biodiversity in the mediterranean biome. Diversity and Distributions 15:188-197.

USFS and BLM. 1994. Record of Decision for amendment to Forest Service and Bureau of Land Management planning documents within the range of the northern spotted owl. USDA Forest Service and USDI Bureau of Land Management, Portland, OR, USA.

Van Kirk, R. W. and S. W. Naman. 2008. Relative effects of climate and water use on base-flow trends in the lower Klamath Basin. Journal of the American Water Resources Association 44:1035-1052.

Van Mantgem, P. J., and D. A. Sarr. 2015. Structure, diversity, and biophysical properties of old-growth forests in the Klamath region, USA. Northwest Science 89:170-181.

Van Mantgem, P. J., et al. (10 co-authors). 2009. Widespread increase of tree mortality rates in the western United States. Science 323: 521-524.

Vicuna, S., E. P. Maurer, B. Joyce, J. A. Dracup, and D. Purkey. 2007. The sensitivity of California water resources to climate change scenarios. Journal of the American Water Resources Association 43:482-498.

Vose, R. S., D. R. Easterling, and B. Gleason. 2005. Maximum and minimum temperature trends for the globe: An update through 2004. Geophysical Research Letters 32.

Westerling, A. L., B. P. Bryant, H. K. Preisler, T. P. Holmes, H. Hidalgo, T. Das, and S. Shrestha 2011. Climate Change and Growth Scenarios for California Wildfire. Climatic Change 109 (s1):445-463.

Westerling, A. L., and B. Bryant. 2006. Climate change and wildfire in and around California: fire modeling and loss modeling. Report from the California Climate Change Center to the California Energy Commission. CEC-500-2006-190-SF.

Westerling, A. L., H. Hidalgo, D. R. Cayan, and T. Swetnam. 2006. Warming and earlier spring increases western U.S. forest wildfire activity. Science 313 (5789):940-943.

Whitlock, C., S. L. Shafer, and J. Marlon. 2003. The role of vegetation change in shaping past and future fire regimes in the northwest U.S. and the implications for ecosystem management. Forest Ecology and Management 178: 5-21.

Williams, A. P., C. D. Allen, A. K. Macalady, D. Griffin, C. A. Woodhouse, D. M. Meko, T. W. Swetnam, S. A. Rauscher, R. Seager, H. D. Grissino-Mayer, J. S. Dean, E. R. Cook, C. Gangodagamage, M. Cai, and N. G. McDowell. 2012. Temperature as a potent driver of regional forest drought stress and tree mortality. Nature Climate Change 3:292-297.

Wimberly, M. C., and Z. Liu. 2014. Interactions of climate, fire, and management in future forests of the Pacific Northwest. Forest Ecology and Management 327:270-279.

Wimberly, M. C., M. A. Cochrane, A. D. Baer, and K. Pabst. 2009. Assessing fuel treatment effectiveness using satellite imagery and spatial statistics. Ecological Applications 19:1377-1384.

WRCC. 2015. California climate data archive. Data obtained from Western Regional Climate Center. Western Regional Climate Center website (last accessed on 6 January, 2016).

Wright, S. A., and D. H. Schoellhamer. 2004. Trends in the sediment yield of the Sacramento River, California, 1957-2001. San Francisco Estuary and Watershed Science 2(2). Report

Zhu, T., M. W. Jenkins, and J. R. Lund. 2005. Estimated impacts of climate warming on California water availability under twelve future climate scenarios. Journal of the American Water Resources Association 41:1027-1038.

Appendix A. Weather Station Information

Weather stations were selected for inclusion based on their location relative to the Shasta-Trinity National Forest (SHF) and the length and completeness of their records. It is important to note that some of these weather stations are found outside of and below the SHF. Temperature and precipitation data collection periods ranged from 23 to 104 years (with between 0 and 10 years of missing data). See Table A1 for station locations, 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)
Shasta Dam	1070	40° 43' N	122° 25' W	within SHF	1944-2015 (temp) 1943-2014 (precip)	0/6
Weaverville	2050	40° 44’ N	122° 56’ W	1 mile S	1913-2009 (temp)	10/na
Whiskeytown Reservoir	1310	40° 37’ N	122° 32' W	within 2 miles	1961-2015 (temp) 1960-2014 (precip)	1/9
McCloud	3280	41° 15' N	122° 08' W	within 2 miles	1911-2015 (temp) 1924-2003 (precip)	2/10
Mt Shasta	3590	41° 19' N	122° 19' W	8 miles	1988-2012 (temp) 1988-2011 (precip)	1/1