National Park Service
U.S. Department of the Interior

Lassen Peak, Lassen Volcanic National Park, April 10, 2017, photo by P. Gonzalez

Climate Change in Lassen Volcanic National Park, California, USA

Patrick Gonzalez, Ph.D., U.S. National Park Service and University of California, Berkeley
Whitney B. Reiner, University of California, Berkeley

Natural Resource Stewardship and Science
U.S. National Park Service
131 Mulford Hall
University of California, Berkeley
Berkeley, CA 94720-3114 USA

July 31, 2017

Climate Change in Lassen Volcanic National Park, California, USA

Patrick Gonzalez and Whitney B. Reiner

Abstract

Greenhouse gas emissions from cars, power plants, deforestation, and other human activities have caused global climate change and widespread impacts on physical and ecological systems. To assist in the integration of climate change science into resource management in Lassen Volcanic National Park, this report presents: (1) historical and projected climate trends for the park, from original analyses at 800 meter spatial resolution, (2) information on historical impacts, future vulnerabilities, and ecosystem carbon, from a scientific literature review focusing on research conducted in the park, and (3) ecosystem carbon storage and changes in the park, from original analyses at 30 meter spatial resolution. Average January temperature from 1950 to 2010 increased at a statistically significant rate of 3 ± 1ºC (5 ± 1.8ºF.) per century (mean ± standard error) for the area within park boundaries. Annual average temperature and total annual precipitation from 1950 to 2010 showed no statistically significant trends. Published field research that includes data from the park has detected changes that have been attributed in part to human-caused climate change. These impacts include tree dieback and wildfire increases. If the world does not reduce greenhouse gas emissions, modeling under the four emissions scenarios of the Intergovernmental Panel on Climate Change project annual average temperature increases of up to 4.6 ± 0.9ºC (8.3 ± 1.6º F.) (mean ± standard deviation) from 2000 to 2100 for the park. Climate models project an increase of total annual precipitation, but hotter temperatures would reduce snowpack and raise the probability of drought. Published research that covers the southern Cascades identifies numerous vulnerabilities to continued climate change, including further increases in wildfire, increased mortality of red fir (*Abies magnifica*) and whitebark pine (*Pinus albicaulis*), upslope biome shifts, and potential extirpation of the American pika (*Ochotona princeps*). National park ecosystems can help to naturally reduce climate change by storing carbon. Aboveground vegetation in the park stores an amount of carbon equivalent to what 600 000 ± 400 000 Americans (mean ± 95% confidence interval) emit in one year. From 2001 to 2010, the aboveground ecosystem carbon stock in the park fell 6 ± 3%, with most of the loss from areas that burned in wildfire, where a century of fire suppression has caused an unnatural buildup of fuels.

Introduction

Greenhouse gas emissions from power plants, motor vehicles, deforestation, and other human activities have increased temperatures around the world and caused other changes in climate in the 20th and early 21st centuries (Intergovernmental Panel on Climate Change (IPCC) 2013). Field measurements show that climate change is fundamentally altering ecosystems by contributing to wildlife extinctions, shifting vegetation biomes, and causing other changes globally (IPCC 2014) and in U.S. national parks (Gonzalez 2017). To assist in the integration of climate change science into management of resources in Lassen Volcanic National Park (N.P.) (Figure 1), this report presents results of original spatial analyses of historical and projected climate change and ecosystem carbon and an assessment of published research on historical impacts of climate change, future vulnerabilities, and ecosystem carbon.

Methods

In this report, spatial analyses of historical climate trends (Wang et al., in preparation) use previously published climate data layers at 800 meter (m) spatial resolution, derived from point weather station measurements using the Parameter-elevation Relationships on Independent Slopes Model (PRISM; Daly et al. 2008). PRISM uses elevation and topography to interpolate (calculate intermediate values) climate in the spaces among weather stations, which are the points in the data set tied to field measurements. This report summarizes results by giving trends for the entire area of the park, within its boundaries, as a single unit.

Linear regression of temperature and precipitation time series gives the historical climate trends, with the statistical probability of significance corrected for temporal autocorrelation. The period starting in 1950 gives a more robust time series than the period starting in 1895 because the U.S. Government established a substantial number of weather stations in the late 1940s and the weather station network has been relatively stable since then. Spatial data from the longer period relies on fewer weather stations and a network that changed irregularly before the 1940s.

Spatial analyses of future projections (Wang et al., in preparation) use output of all available general circulation models (GCMs) of the atmosphere in the Coupled Model Intercomparison

Project Phase 5 data set developed for the most recent IPCC report (IPCC 2013). The coarse GCM output, at spatial resolutions of up to 200 km, has been downscaled to 800 m spatial resolution using bias correction and spatial disaggregation (Wood et al. 2004).

Information on historical impacts of climate change and future vulnerabilities comes from a search of the Thomson Reuters Web of Science scientific literature database for published research that used field data from Lassen Volcanic N.P. or research that covered the park as part of a broader area of analysis.

Spatial analyses of ecosystem carbon use published data on carbon stocks and changes (Gonzalez et al. 2015) from analyses of vegetation cover from satellite-derived Landfire data, vegetation productivity from Modis satellite data, and tree biomass from USDA Forest Service field inventories.

Historical Climate Trends

Monthly average temperature of the area within park boundaries showed statistically significant rates of increase in the period 1950-2010 for two months: January, 3 ± 1ºC (5 ± 1.8ºF.) per century (mean ± standard error), and March, 3.5 ± 1ºC (6.3 ± 1.8ºF.) per century (Table 1). High rates of heating in the spring are attributable to emissions of greenhouse gases from human activities (Bonfils et al. 2008, IPCC 2013).

Annual average temperature of the area within park boundaries showed no statistically significant change (Figure 2). The southern Cascades region is one of a few anomalous areas of the world where mean annual temperature has not yet increased, although it has increased in some areas (Figure 3). In the park, temperature has increased in Warner Valley (south-central part of the park) and Fantastic Lava Beds (northeast part of the park). The anomalous lack of significant heating in the southern Cascades may be due to wind changes from differences in heating with central California (Lebassi et al. 2009) or due to the ocean cycles of the Pacific Decadal Oscillation (Cordero et al. 2011), but the cause remains undetermined.

The park hosts two National Weather Service (NWS) Cooperative Observer Program stations, at park headquarters in Mineral, CA, and at Manzanita Lake. Although the data records at the two stations begin, respectively, in 1927 and 1949, wide data gaps starting, respectively, in 2004 and 2002 make the time series currently unusable for long-term trend analysis after those years. Continued data collection at the stations could provide information for the park that is unique because of the length of the time series. Climate data enables researchers to analyze historical impacts of climate change and future vulnerabilities of natural and cultural resources and park infrastructure.

The park hosts five other weather stations that were established less than 30 years ago at the following locations, with the operator identified for each: (1) park headquarters, California Department of Water Resources, (2) Lake Helen, below Lassen Peak, Pacific Gas and Electric Company, (3) Hat Mountain, Remote Automated Weather Station, National Interagency Fire Center, (4) Manzanita Lake, California Air Resources Board, (5) Manzanita Lake, National Park Service, Air Resources Division. In addition, Lake Helen and Manzanita Lake have snow courses, long sampling sites for measuring snow depth and water content in the winter.

Other NWS stations across the western U.S. have provided data for the detection of temperature increases and attribution to emissions from human activities. These include increases in winter minimum temperatures at rates of 2.8 to 4.3ºC per century (Barnett et al. 2008, Bonfils et al. 2008) and an advance of spring warmth a week from 1950 to 2005 (Ault et al. 2011).

Total annual precipitation of the area within park boundaries decreased slightly in the period 1950-2010, but the change was not statistically significant (Figure 4, Table 2). Precipitation has decreased most in the Warner Valley (south-central part of the park) and in the northwest part of the park (Figure 5). The precipitation graph (Figure 4) shows the annual data for 2011-2013, the first years of a severe California drought (described further below). Further analysis of precipitation that added these three years, not included in the original 1950-2010 analysis, found no statistically significant trend for the period 1950-2013. Climate water deficit (the difference between precipitation and actual evapotranspiration) decreased slightly across the southern Cascades between the periods 1900-1939 and 1970-2009 (time periods used in the original publication), indicating that conditions became slightly less arid (Rapacciuolo et al. 2014).

NWS stations, not including the two stations in the park, and Natural Resources Conservation

Service snow courses, outside the park, across the western U.S. have provided data for the detection of changes in snow and attribution of the main cause to the increased heat of climate change. In the southern Cascades and northern Sierra Nevada, snow cover declined by one-fifth from 1950 to 1999 (Bonfils et al. 2008). Across the western U.S., the water content of snowpack declined 10 to 20% from 1982 to 2016 (Fyfe et al. 2017) and the ratio of snow to rain decreased at rates of -24 to -79% per century from 1950 to 1999 (Barnett et al. 2008, Pierce et al. 2008). Snow can cover much of the park in the spring. Modis remote sensing of snow cover (Hall et al. 2017) shows that half of the area of the park had snow cover at least every other year from 2000 to 2016 (Figure 6).

The California Drought of 2011-2016 was initiated by a low period in the natural precipitation cycle (Mao et al. 2015, Seager et al. 2015) and intensified by the record heat of human-caused climate change (Diffenbaugh et al. 2015, Griffin and Anchukaitis 2014, Luo et al. 2017, Shukla et al. 2015, Williams et al. 2015). The third lowest 12-month precipitation total and the hottest annual average temperature in the period 1896-2014 occurred at the same time (Diffenbaugh et al. 2015). Analyses of the Palmer Drought Severity Index (PDSI), an indicator of near-surface soil moisture, for the period 1901-2014 indicate that 2014 was drier than average in the park (Williams et al. 2015). While the probability of low precipitation years has not increased, the hotter temperatures caused by human-caused climate change have increased the probabilities of drought through increased probabilities of high temperature and low precipitation coinciding in the same year (Diffenbaugh et al. 2015). Through increased temperature, human-caused climate change may have accounted for one-tenth to one-fifth of the soil dryness of the 2012-2016 California drought (Williams et al. 2015). During the California Drought, snow cover completely disappeared by early spring across 90% of the area of the park (Figure 7).

In addition to intensifying droughts, climate change is increasing the frequency of the opposite precipitation extreme of heavy storms. National Oceanic and Atmospheric Administration (NOAA) analyses of weather station data show an increase of heavy storms in a six-state region extending from California to New Mexico. The decade 1991-2000 experienced an increase of 25% in five-year storms (a storm with more precipitation than any other storm in five years), compared to the 1901-1960 average (Walsh et al. 2014). In addition, the heaviest storms became even heavier, with a 5% increase in the amount of precipitation falling in the heaviest 1% of all storm days from 1958 to 2012 (Walsh et al. 2014).

Historical Impacts

Changes detected in Lassen Volcanic N.P. and attributed to human-caused climate change

Published research using field data from Lassen Volcanic N.P. has detected ecological changes statistically significantly different from historic variation and attributed the cause of those changes to human-caused climate change more than other factors.

Wildfire increase Analyses of climate and wildfire across the western United States, using data from Lassen Volcanic N.P. and other areas, found that climate change doubled the area burned by wildfire from 1984 to 2015 compared to what would have burned without climate change (Abatzoglou and Williams 2016). Temperature and precipitation determined burned area in the western U.S. from 1916 to 2003 more than fire suppression, local fire management, or other non-climate factors (Littell et al. 2009). Specific climate factors that controlled fire in the Sierra Nevada and southern Cascades included the drought severity (a combination of temperature and precipitation) in the summer and precipitation in the preceding year's winter. Reconstruction of fires of the past 400 to 3000 years in the western U.S. (Marlon et al. 2012, Trouet et al. 2010) confirm that temperature and drought are the dominant factors explaining fire occurrence. The increased heat of climate change has intensified drought (Williams et al. 2015), reduced snowpack (Fyfe et al. 2017, Pierce et al. 2008), and caused spring warmth to occur earlier (Ault et al. 2011). As a result, forests have dried earlier and for longer periods of time (Asner et al. 2016, Clark et al. 2016), driving the wildfire increase (Abatzoglou and Williams 2016, Westerling 2016). In addition, historic fire suppression policies have caused unnatural accumulations of fuel in the park (Taylor 2000) and across the western U.S. (Hessburg et al. 2016, Stephens and Ruth 2005). Consequently, wildfires in California emitted more carbon from 2001 to 2010 than the forests absorbed through regrowth (Gonzalez et al. 2015).

Bark beetle increase Analyses of climate and bark beetle infestations across the western United States, using data from Lassen Volcanic N.P. and other areas, showed that infestations killed 7% of western U.S. forest area from 1979 to 2012 (Hicke et al. 2016), driven by winter warming, which allows beetles to survive longer and at higher elevations

(Barnett et al. 2008, Bonfils et al. 2008, Raffa et al. 2008). Climate change has caused bark beetle outbreaks to reach their greatest extent in North America in 125 years (Raffa et al. 2008). Bark beetles have killed Jeffrey pine (*Pinus jeffreyi*) in the park and elsewhere in California (Bentz et al. 2010).

Tree dieback Tracking of trees in permanent old-growth conifer forest plots across the western U.S., including plots in Lassen Volcanic N.P., found a statistically significant doubling of tree mortality rates (fraction of all trees dying) between 1955 and 2007 (van Mantgem et al. 2009). Analyses of potential causes found that the increased rate of tree mortality was due more to the heat of climate change and increased wildfire and bark beetle infestations, both attributable to climate change, (Abatzoglou and Williams 2016, Hicke et al. 2016, Raffa et al. 2008), than to other factors, including increased tree densities after fire suppression, competition among trees for light and water, forest fragmentation, or air pollution (van Mantgem et al. 2009). From 2012 to 2014, the first years of the California drought, which was intensified by climate change, forest canopy water content in the southern Cascades fell by ~10%, as estimated by remote sensing (Asner et al. 2016). Drying of the tree canopy contributes substantially to tree dieback (Allen et al. 2010).

Changes detected in the southern Cascades and attributed to human-caused climate change

Published research using data from the region, but not from Lassen Volcanic N.P., has detected changes attributable to climate change.

Earlier stream flow Measurements of stream flow at U.S. Geological Survey stream gauges across the western U.S. detected advances of peak stream flow (center of timing of annual flow) of a week from 1950 to 1999 and analyses of causal factors attribute the cause to earlier snowmelt from the increased heat of climate change (Barnett et al. 2008). Sacramento River flow and stream flow in the Sierra Nevada advanced 5 to 10 days earlier in the year from 1920 to 2014 (Dudley et al. 2017). When snow melts early, the peak stream flow, which occurs in the spring, moves earlier in the year. Meltwater that may have fed streams and rivers through late spring and early summer flows earlier in the year, leading to potentially longer periods of low flow or dry conditions.

Bird range shifts Analyses of Audubon Christmas Bird Count data across the U.S., including counts west of the park in Redding, CA, detected a northward shift of winter ranges of a set of 254 bird species at an average rate of 0.5 ± 0.3 km per year from 1975 to 2004, attributable more to climate change than other factors (La Sorte and Thompson 2007). Further analyses demonstrate poleward shifts in winter distributions of six raptor species listed by the NPS Inventory and Monitoring Program (NPS 2017) as breeding in the park (Red-tailed Hawk (*Buteo jamaicensis*), Golden Eagle (*Aquila chrysaetos*)), or observed in the park (American Kestrel (*Falco sparverius*), Prairie Falcon (*Falco mexicanus*), Rough-legged Hawk (*Buteo lagopus*), Northern Harrier (*Circus cyaneus*)) (Paprocki et al. 2014).

Changes consistent with, but not formally attributed to human climate change

Other research has found changes consistent with human-caused climate change, but either not detected as statistically significantly different than historical variability or, if detected, not analyzed to formally attribute the cause of the change.

Tree upslope shifts Field surveys and measurements of mountain hemlock (*Tsuga mertensiana*) trees in 24 plots in subalpine areas of the park found upslope expansion of trees, especially since 1880 (Taylor 1995). Seedling establishment was correlated to annual and summer temperature at the weather station in Mineral, CA.

Invasive plants upslope shifts Analyses of plant samples that were collected in California from 1895 to 2009 and preserved in herbaria (botanical collections) found that one-quarter of non-native species shifted upslope, compared to one-ninth of native species (Wolf et al. 2016). This is consistent with greater adaptation of many invasive plants to warmer conditions.

Mammal range shifts Small mammal surveys from 2003 to 2010 followed the Grinnell surveys from 1911 to 1934 of a transect that ran from the foothills west of the park and through the park to end east of the park (Rowe et al. 2015). Ranges of nine of 25 small mammal species showed statistically significant upslope shifts, consistent with upslope shifts of warmer temperatures, but four showed statistically significant downslope shift. The pinyon mouse (*Peromyscus truei*) showed the clearest upslope shift, with range expansion at its upper limit and contraction at its lower limit. The American water shrew (*Sorex palustris*) showed the clearest downslope shift. Analyses of the Grinnell transects in Lassen Volcanic, Sequoia, and Yosemite National Parks found that Belding's ground squirrel (*Urocitellus beldingi*) was extirpated from 42% of sites as snow cover decreased (Morelli et al. 2012) and body size increased with lengthening of the food plant growing season (Eastman et al. 2012).

Bird range shifts Bird resurveys from 2003 to 2008 of the Grinnell surveys from 1911 to 1929 in Lassen Volcanic, Sequoia, and Yosemite National Parks found elevation shifts of the ranges for a majority of bird species examined, with shifts tracking temperature and precipitation changes up- or downslope (Tingley et al. 2009, 2012). The bird data was also part of a global analysis of plant and animal species in sites in montane ecosystems (Gibson-Reinemer et al. 2015) which found species turnover of 12% per decade, related to increased temperatures at the sites.

Future Climate Projections

IPCC has coordinated research groups to project possible future climates under four defined greenhouse gas emissions scenarios, called representative concentration pathways (RCPs; Moss et al. 2010). The four emissions scenarios are RCP2.6 (reduced emissions from increased energy efficiency and installation of renewable energy), RCP4.5 (low emissions), RCP6.0 (high emissions, somewhat lower than continued current practices), and RCP8.5 (highest emissions due to lack of emissions reductions).

If we do not reduce greenhouse gas emissions by 40-70%, GCMs project substantial warming and slight increases in precipitation in the park by 2100. The temperature and precipitation projections from 33 GCMs form a cloud of potential future climates (Figure 8). GCMs project potential increases in annual average temperature of the area within park boundaries by 1.6 to 2.5ºC (2.9 to 4.5ºF.) by 2050 (Table 3) and up 4.6ºC (8.3ºF.) by 2100 (Table 4). Projected temperature increases do not show much spatial variation across the park (Figure 9). Models project the greatest temperature increases in the summer (Tables 3, 4).

The average of the ensemble of GCMs projects increased precipitation under all emissions scenarios (Tables 5, 6). The average of the ensemble reflects the central tendency of the projections, but the uncertainty of any single model of future climate can be large. In the region of the park, GCMs do not agree on precipitation projections, with over half projecting increases, but many projecting decreases (Figure 8). Projected precipitation increases tend to increase from west to east, but do not show much spatial variation across the park (Figure 10). GCMs tend to project increases in winter but slight decreases in autumn (Tables 5, 6).

Continued increases in winter and spring heat may reduce snowpack (April 1 snow water equivalent) in the park by two-thirds under a high emissions scenario or one-third under a low emissions scenario (Curtis et al. 2014). This projection takes account of cold-air pooling in north-facing slopes, ravines, and other shaded areas. Heat may reduce the number of snow days in the Sierra Nevada east of the park by one-third from 2005 to 2050 under the highest emissions scenario (Lute et al. 2015).

Even if precipitation increases, temperature increases may overcome any cooling effects, leading to increased evapotranspiration and increased aridity, expressed as increased climate water deficit (difference between precipitation and actual evapotranspiration) and decreased soil moisture. Modeling of climate water deficit with one GCM under high emissions projects more arid conditions by 2100 AD in the southern Cascades (Thorne et al. 2015).

Hotter temperatures caused by human climate change have increased the probabilities of drought through increased probabilities of high temperature and low precipitation co-occurring in a single year (Diffenbaugh et al. 2015). Under the highest emissions scenario, additional warming may increase the probability that, by 2030, any annual dry period co-occurs with drought-level heat (Diffenbaugh et al. 2015).

Projections indicate potential changes in the frequency of extreme temperature and precipitation events. For northern California, under the highest emissions scenario, models project up to 10 more days per year with a maximum temperature >35°C (95°F.) and an increase in 20-year storms (a storm with more precipitation than any other storm in 20 years) to once every five to six years (Walsh et al. 2014).

Future Vulnerabilities

If we do not reduce greenhouse gas emissions from, continued climate change could increase the vulnerability of park resources (IPCC 2013). Published research on Lassen Volcanic N.P. or the region has identified numerous vulnerabilities.

Vegetation

Wildfire increase Under high emissions, climate change could double or triple burned area in the southern Cascades by 2100, compared to 1990 (Westerling et al. 2011) and increase fire frequencies by one-quarter to one-third by 2050, compared to 2000 (Mann et al. 2016). Under low emissions, burned area across the state of California could increase just slightly (Westerling et al. 2011). This demonstrates the positive impact of energy conservation, renewable energy, and other actions to reduce greenhouse gas emissions.

In the southern Cascades, because models diverge on whether precipitation may increase or decrease, two broad fire regimes (Littell et al. 2009) could occur under a high emissions scenario:

1. Dry-fire future – hotter and drier climate, increased fire frequency, fire limited by vegetation, potential biome change of forest to grassland after a fire due to low natural regeneration, high carbon emissions.
2. Intense-fire future – hotter and wetter climate, more vegetation, increased fire frequency and intensity, fire limited by climate, higher carbon emissions.

These are two broad categories that each encompass a range of fire conditions. On the ground, gradients of temperature, precipitation, and climate water deficit (difference between precipitation and actual evapotranspiration) would generate varied fire conditions. Furthermore, because climate change, vegetation, and ignitions vary across the landscape, potential fire frequency may show high spatial variability (Gonzalez et al. 2010, Moritz et al. 2012, Westerling et al. 2011). Consequently, future fire regimes could vary in patches across the landscape, with different regimes manifesting themselves in adjacent forest patches. Managed wildland fire and prescribed burning can reduce the potential for crown fires in both regimes (Stephens et al. 2013). The section of this report on carbon, below, summarizes the potential future implications of fire for ecosystem carbon.

Tree dieback from drought and beetle infestations Red fir (*Abies magnifica*), whitebark pine (*Pinus albicaulis*), and Jeffrey pine (*Pinus jeffreyi*) are particularly vulnerable to dying from drought stress (Dolanc et al. 2013). Consequently, projected increases of drought (Diffenbaugh et al. 2013) and reductions of snowfall (Curtis et al. 2014) under climate change would increase the vulnerability of forests in the park to tree dieback.

Red fir requires deep snow in the winter to survive with the snow insulating a tree from wind and dehydration in winter and providing moist conditions that would last into the summer (Barbour et al. 1991). Measurements of a transect of trees in the park found that red fir requires at least 0.8 m of snow in late March (Barbour et al. 1991).

Under a high emissions scenario, bark beetles that kill whitebark pine, Jeffrey pine, and other conifer tree species in the park may be able to survive the entire winter by 2100 (Bentz et al. 2010). Whitebark pine mortality from bark beetles increases as minimum winter temperatures increase and summer precipitation decreases, based on observations in the Rocky Mountains and northern Cascades (Buotte et al. 2017). White pine blister rust, a fungus that has been killing trees in the Rocky Mountains, requires a cool moisture-saturated environment, so vulnerability of whitebark pine to this pathogen decreases under climate change (Sturrock et al. 2011)

Biome shifts Under all emissions scenarios, the southern Cascades region is vulnerable to upslope vegetation shifts at the level of the biome (major vegetation types such as temperate shrubland, conifer forest, or alpine meadow) (Rehfeldt et al. 2012, Langdon and Lawler 2015). The region is moderately vulnerable to the combined effects of biome shifts due to climate change and habitat loss due to land cover change (Gonzalez et al. 2010, Eigenbrod et al. 2015). Projected increases in fire frequency could maintain or expand chaparral area and reduce mixed conifer forest (Lauvaux et al. 2016), with the net effect of a shift of the shrubland biome into the conifer forest biome, altering habitat for plants and wildlife. This biome shift would reverse a historical shift revealed by research on wildfire in chaparral and mixed conifer forest in 1941 and 2005 at six sites in the park (Lauvaux et al. 2016). The research found that fire maintained stands of chaparral within a mixed conifer forest landscape, chaparral burned less frequently than surrounding forest, and small patches of high severity fire created chaparral habitat. Fire suppression drove landscape heterogeneity, leading to declines in chaparral and replacement by forest.

Mountain fen drying Mountain fens (meadows fed by groundwater) at Willow Creek, south of the park, and in Sierra Nevada sites exhibit vulnerability to drying under increased temperatures (Drexler et al. 2013).

Rare plant decrease Low population sizes and restricted ranges make rare plant species inherently more vulnerable to most threats, including climate change (Anacker et al. 2013). An assessment of life history attributes and modeling of species distributions of 156 of the 1625 plant species listed in 2011 as rare or endangered by the California Native Plant Society identified 42 species as extremely or highly vulnerable to a reduction in population due to climate change (Anacker et al. 2013). Only one of the 156 species in the sample, moss phlox (*Phlox muscoides*), is currently present in the park (NPS 2017) and it was assessed as moderately vulnerable. More rare plants that are found in the park but were not included in the sample of 156 species might be vulnerable to climate change.

Invasive plant increase Exotic grass species are generally annuals and are taller and have larger leaves and seeds than native species. Across California, these traits are associated with higher temperatures, confirmed by the prevalence of exotic grass species in warmer areas of the state (Sandel and Dangremond 2012). The southern Cascades region is highly vulnerable to invasive species under climate change due to a combination of the potential for introductions from roads and increased potential for establishment with biome shifts and wildfire changes (Early et al. 2016). For one invasive species, yellow starthistle (*Centaurea solstitialis*), the southern Cascades would continue to provide suitable habitat under a high emissions scenario (Bradley et al. 2009). The increased growth that cheatgrass (*Bromus tectorum*) experiences under warmer and wetter conditions (Boyte et al. 2016) suggests that the park may become more susceptible to invasions under scenarios of greater rainfall. In turn, cheatgrass could increase wildfire frequencies and replace shrubs and trees (Abatzoglou and Kolden 2011).

Earlier bud break Field monitoring of blue elderberry (*Sambucus nigra*) phenology (timing of life cycle events) and climate from 2011 to 2013 at seven national parks in California, including Lassen Volcanic N.P., found that warmer spring temperatures shifted bud break and fruiting earlier in the year (Mazer et al. 2015), a potential future vulnerability for any birds or other wildlife that might depend on the fruit later in the year.

Wildlife

Pika possible extirpation Upslope and poleward shifting of cooler climates and biomes increase the vulnerability of the American pika (*Ochotona princeps*) to losing its habitat (Beever et al. 2011, 2016; Schwalm et al. 2016). Historical records of occurrence from 1898 to 2008 throughout the Great Basin, east of the park, revealed that pika were extirpated from 10 of 25 research sites and that ranges shifted upslope 360 m in elevation, on average (Beever et al. 2011, 2016). Under a high emissions scenario, shifting of habitat makes the pika vulnerable to extirpation in Lassen Volcanic, Sequoia, and Yosemite National Parks (Stewart et al. 2015).

A different study, however, projected that persistence of some habitat in Lassen Volcanic N.P. might allow pika to survive under climate change (Schwalm et al. 2016). Despite barriers to dispersal, analyses of pika fecal samples from the park from 2010 to 2012 found gene flow was relatively high (Castillo et al. 2016). Structurally complex lava flow habitat with forbs may provide refugia under climate change, based on a pika survey in Craters of the Moon National Monument and Preserve, Idaho (Rodhouse et al. 2010).

Modeling across the Great Basin, east of the park, of 39 sites indicated that pika body-heat regulation behavior, include sweating, panting, and retreating to cool interstices, could buffer some effects of climate change (Mathewson et al. 2016). Dietary flexibility could increase adaptive capacity to changes in forage due to climate change (Varner et al. 2016). Analyses of climate and stress hormone metabolites (glucocorticoids) in pika fecal samples from the park and other sites suggest a potential relationship between climate change and chronic stress in pika (Wilkening et al. 2016).

Plague increase Under a high emissions scenario, climate change could increase the risk of plague (caused by the bacterium *Yersinia pestis*) in rodents in the park to up to 80% by 2050, double the current risk (Holt et al. 2009). Increased temperature and precipitation can increase rodent and flea reproduction, leading to the projected increase.

Belding's ground squirrel decrease Under high emissions, upslope and poleward shifting of cooler climates may substantially reduce suitable habitat for Belding's ground squirrel (*Urocitellus beldingi*) (Morelli et al. 2012).

Bat mortality Increasing aridity can reduce bat reproduction (Adams and Hayes 2008). Bats may be disproportionately affected by increased aridity relative to other mammals because small body size and a large surface area-to-volume ratio predisposes them to dehydration through evaporative loss (Adams 2010). This could be higher in species with large ears, such as Townsend's big-eared bats (*Corynorhinus townsendii*) (Gillies et al. 2014), which the NPS Inventory and Monitoring Program lists as possibly present in the park, but unconfirmed (NPS 2017). Projections of bat distributions under climate change in the midwestern U.S. indicate vulnerabilities of bats to upslope or northward shifting of maternity colonies as temperature increases (Loeb and Winters 2013) and to earlier emergence from hibernacula, before insect prey become abundant (Meyer et al. 2016).

White nose syndrome is a disease caused by an invasive fungus (*Pseudogymnoascus destructans*), which, in the eastern U.S. has infected and killed big brown bats (*Eptesicus fuscus*), listed as present in the park but uncommon, and little brown bats (*Myotis lucifugus*), common in the park (NPS 2017). White nose syndrome is associated with precipitation frequency (30% of days with any precipitation), annual temperature (38-40ºC), mean temperature of the wettest quarter (2-17ºC), and precipitation during the wettest month (<100 mm) (Flory et al. 2012). White nose syndrome is currently not present in the park, but under historical and projected climate, some conditions are suitable in the park for the disease. The speed and severity of the historic spread of white nose syndrome suggest, however, that factors other than climate are more influential in its expansion.

Spotted owl decline Field research from 1985 to 2013 on northern spotted owls (*Strix occidentalis caurina*), in Del Norte and Humboldt Counties, California, and Oregon and Washington found that recruitment (survival of young owls into adulthood) was most highly correlated to low winter temperature and precipitation (Dugger et al. 2016). Field studies and modeling of northern spotted owls in Oregon and Washington found that warmer wetter winters and hotter drier summers could decrease owl survival (Glenn et al. 2011). Northern spotted owls live in forests with dense canopies of mature and old-growth trees, abundant logs, standing snags, and live trees with broken tops. They prefer older forests with multi-layered canopies of conifer trees of varying species, size, and age, with open space to allow flight under the canopy. Potential changes in forest cover due to wildfire, bark beetle infestations, dieback, and biome shifts could reduce spotted owl habitat.

Cascades frog decline An assessment of 358 vertebrate taxa in California listed one amphibian, the Cascades frog (*Rana cascadae*) as highly vulnerable to increased mortality due to drought (California Department of Fish and Wildlife 2016). Drying of ponds and meadows can strand eggs, tadpoles, and adult frogs (Pope et al. 2014). Surveys in the park have not found Cascades frogs since 2008 (Pope et al. 2014).

Trout decrease Coldwater fish are vulnerable to loss of suitable habitat due to potential warming of streamwaters (Lynch et al. 2016). Across the Rocky Mountains and Great Basin, habitat for nonnative brook trout (*Salvelinus fontinalis*) and brown trout (*Salmo trutta*) could decline, respectively, by three-quarters and by one-half (Wenger et al. 2011), suggesting possible vulnerability in the park.

Physical Resources

Air pollution increase Vehicle exhaust and other combustion sources, combined with hotter temperatures under climate change, could increase fine particulate matter (diameter <2.5 µm) in the park under the highest emissions scenario (Van Martin et al. 2015).

Carbon

Growing vegetation naturally removes carbon from the atmosphere, reducing the magnitude of climate change. Conversely, deforestation, wildfire, and other agents of tree mortality emit carbon to the atmosphere, exacerbating climate change. Determining the balance between ecosystem carbon emissions to the atmosphere and removals from the atmosphere is essential for tracking the role of ecosystems in climate change (IPCC 2013).

Analyses of Landsat remote sensing and field measurements of biomass across the state of California have produced estimates of the carbon in aboveground vegetation for the grasslands, woodlands, forests, and other non-agricultural and non-urban areas of the state at 30 m spatial resolution (Gonzalez et al. 2015). Monte Carlo analyses of error in tree measurements, remote sensing, and the carbon fraction of biomass quantified the uncertainty of carbon stock change estimates. Validation of the carbon stock estimates by independent stock estimates derived from measurements at field sites found that the new results were close to field-derived estimates.

In 2010, aboveground live vegetation in Lassen Volcanic N.P. contained 3.4 ± 2.1 million tons of carbon (mean ± 95% confidence interval) (Table 7; Gonzalez et al. 2015). This stock is equivalent to the greenhouse gases emitted by 600 000 ± 400 000 Americans in just one year. The highest carbon densities in the park occur in red fir (*Abies magnifica*) forests, whose tallest stands in the park store 470 ± 140 tons per hectare (Figure 11).

From 2001 to 2010, aboveground vegetation carbon increased on 4% of the land area of Lassen Volcanic N.P. and decreased on 15% (Figure 12; Gonzalez et al. 2015). The carbon increases result from increased vegetation cover and tree height. The carbon decreases occurred mainly in areas burned by wildfire. Across the western U.S., a century of unnatural fire suppression (Hessburg et al. 2016, Stephens and Ruth 2005) has depressed fire frequencies below natural levels and caused substantial increases in the densities of small-diameter trees and accumulations of dead matter that serve as fuel (Stephens et al. 2007, Marlon et al. 2012).

A short-term emissions increase may be difficult to avoid because NPS and other agencies use wildland fire and prescribed burning to restore ecologically appropriate fire regimes to the land. Moreover, if we do not reduce greenhouse gas emissions, projections indicate that climate change, under a high emissions scenario, could increase fire frequencies by up to a third by 2050 (Mann et al. 2016) and double or triple burned area in the region by 2085 (Westerling et al. 2011). Although managed wildland fire and prescribed burning can release a pulse of carbon in the short-term, they can augment carbon storage and reduce net greenhouse gas emissions in the long-term by promoting the replacement of dense stands of small trees with open stands of large, old trees (Hurteau and North 2009, Hurteau and Brooks 2011, Earles et al. 2014, Hurteau et al. 2014).

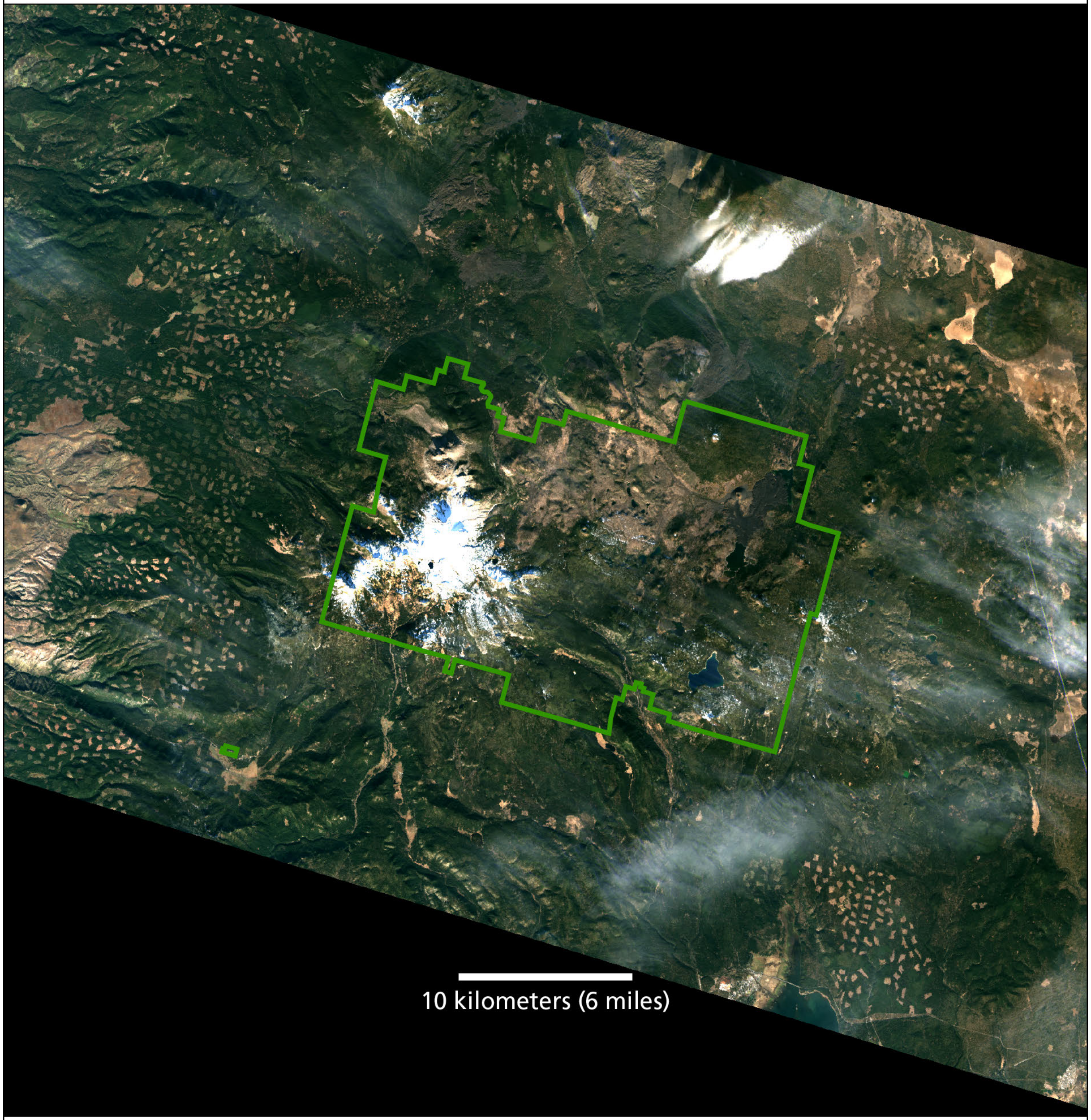
As part of the NPS Climate Friendly Parks program, Lassen Volcanic N.P. has conducted an inventory of greenhouse gas emissions from fossil fuel use by park operations and visitors (NPS 2011). The analysis estimated total emissions in 2007 of 770 million tons carbon, of which 23% came from park operations. Visitors driving passenger vehicles accounted for 72% of total emissions. The *Lassen Volcanic National Park Action Plan* (NPS 2011) identified energy conservation, waste management, and other actions to reduce emissions from park operations.

Acknowledgements

Thanks to Jason Mateljak and Elizabeth Hale (Lassen Volcanic National Park) and Alice Chung-MacCoubrey, Eric Dinger, and Sean Smith (NPS Inventory and Monitoring, Klamath Network), for detailed and helpful input. Thanks also to Steve Buckley and Michael Magnuson (Lassen Volcanic National Park) for informative discussions.

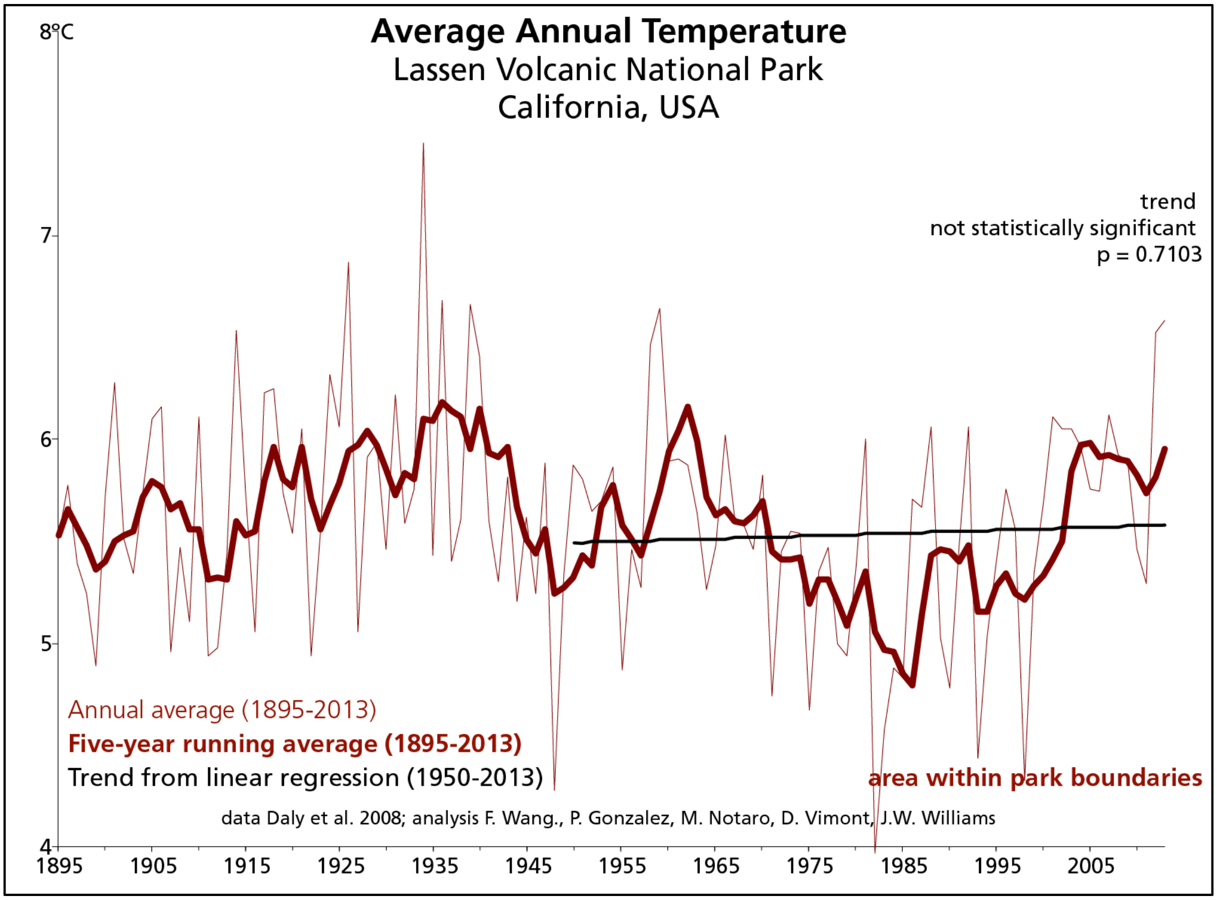
Figure 1.

Lassen Volcanic National Park, California, USA



November 18, 2016
Real Color Image
Data Landsat, U.S. Geological Survey; Analysis P. Gonzalez

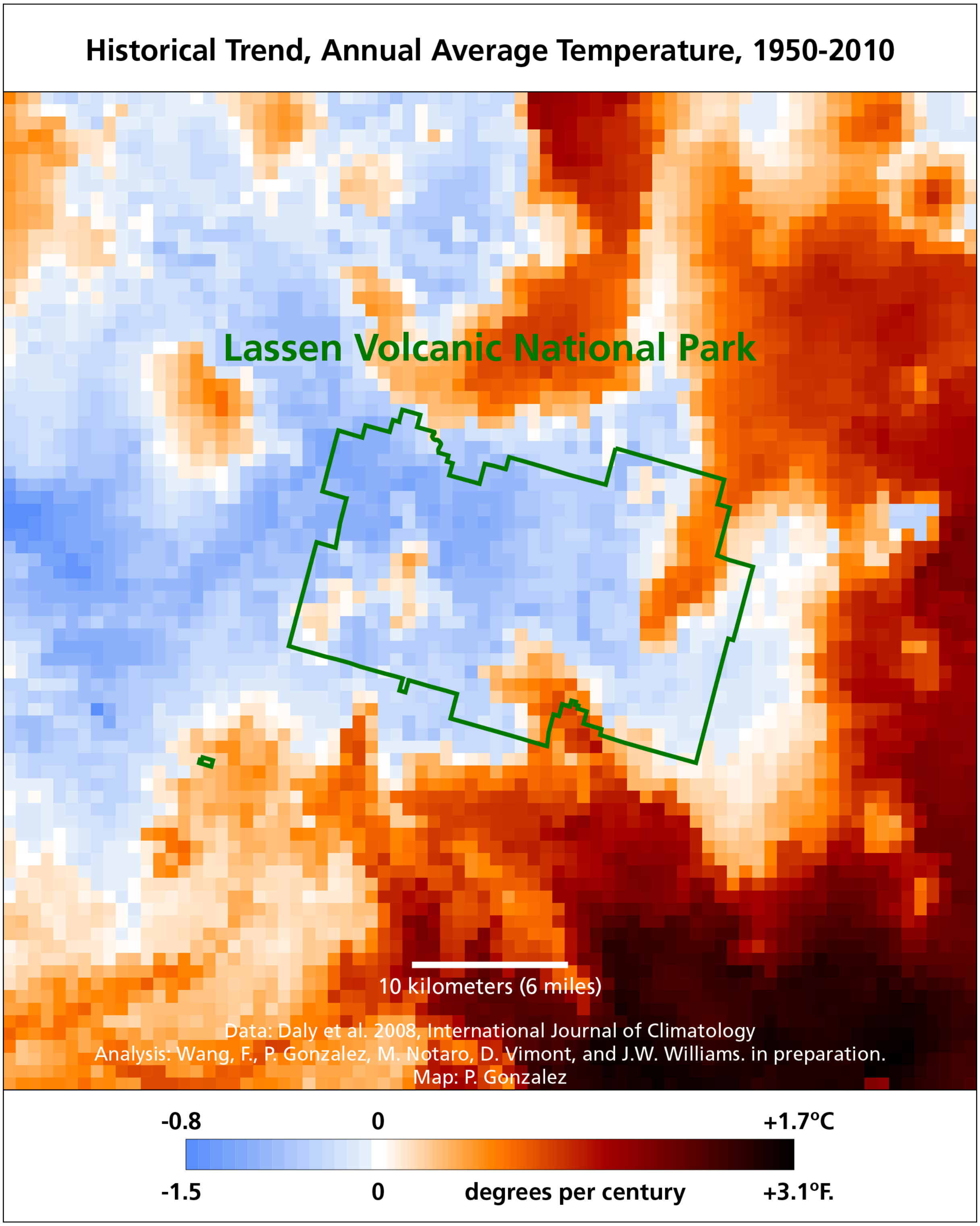
Figure 2.



Main conclusion: Average annual temperature has increased,

but the rate has not been statistically significant.

Figure 3.

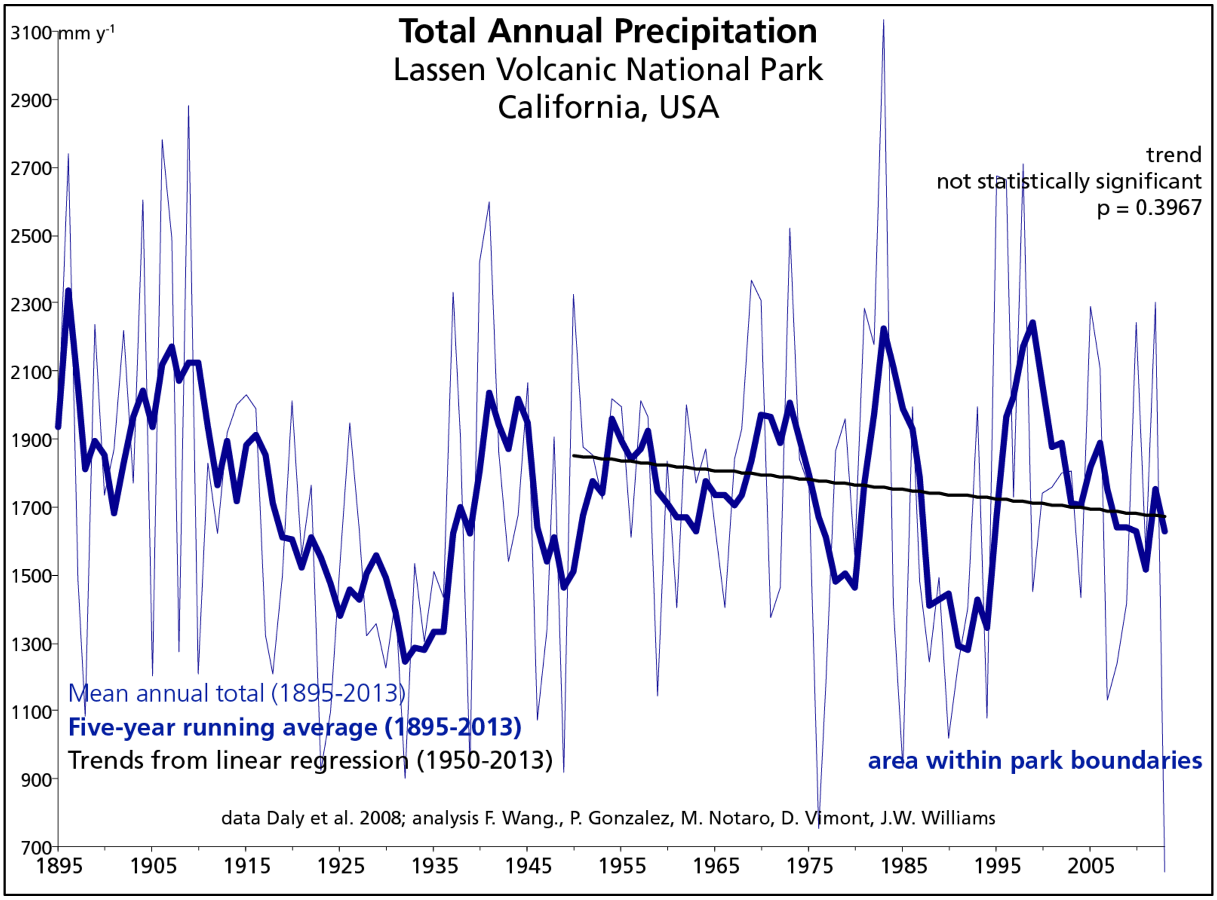


Historical Trend, Annual Average Temperature, 1950-2010

Data: Daly et al. 2008, International Journal of Climatology
Analysis: Wang, F., P. Gonzalez, M. Notaro, D. Vimont, and J.W. Williams. in preparation.
Map: P. Gonzalez

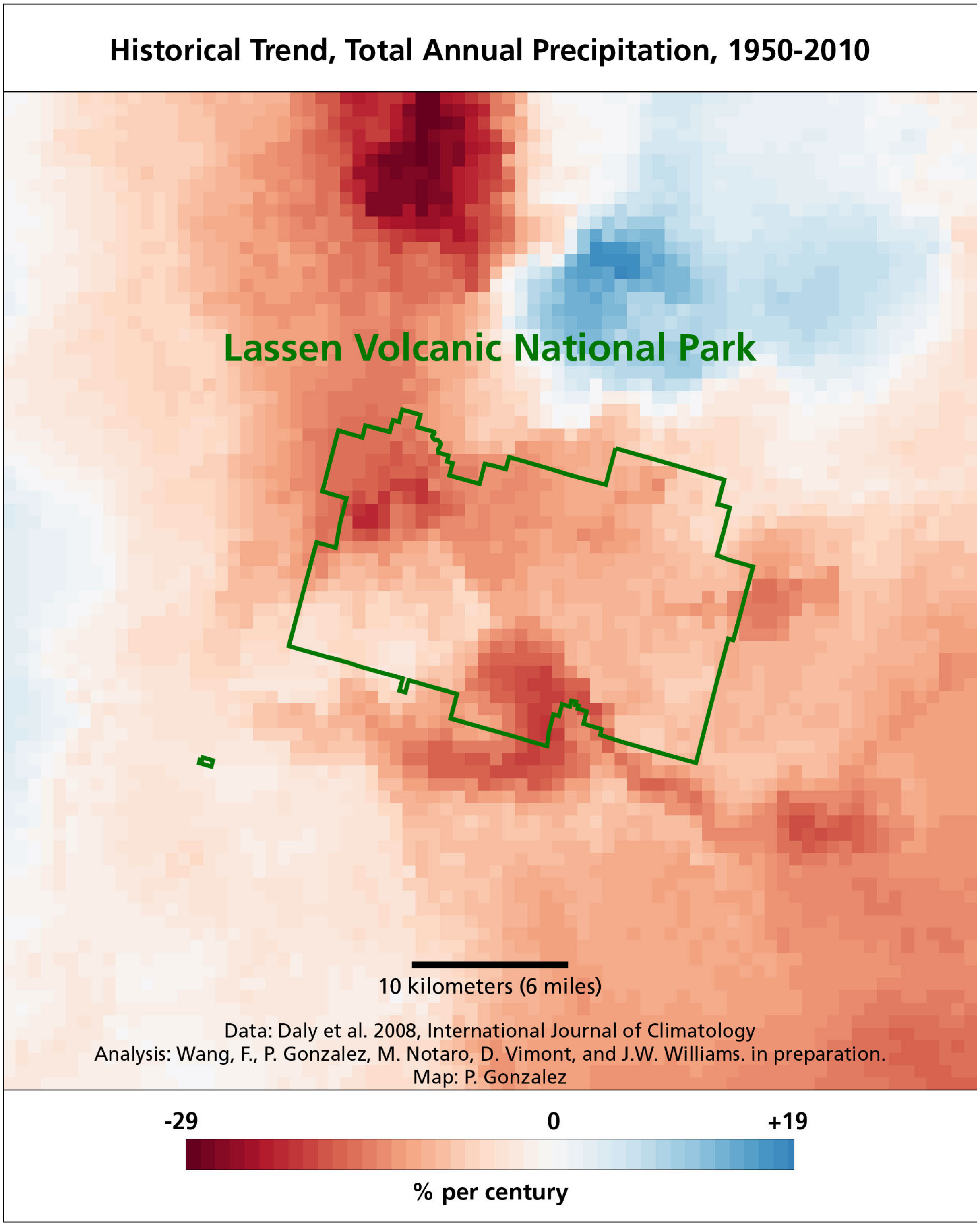
Main conclusion: The park is in an anomalous area of northern California of no temperature increase, except for Warner Valley and the area of the Fantastic Lava Beds.

Figure 4.



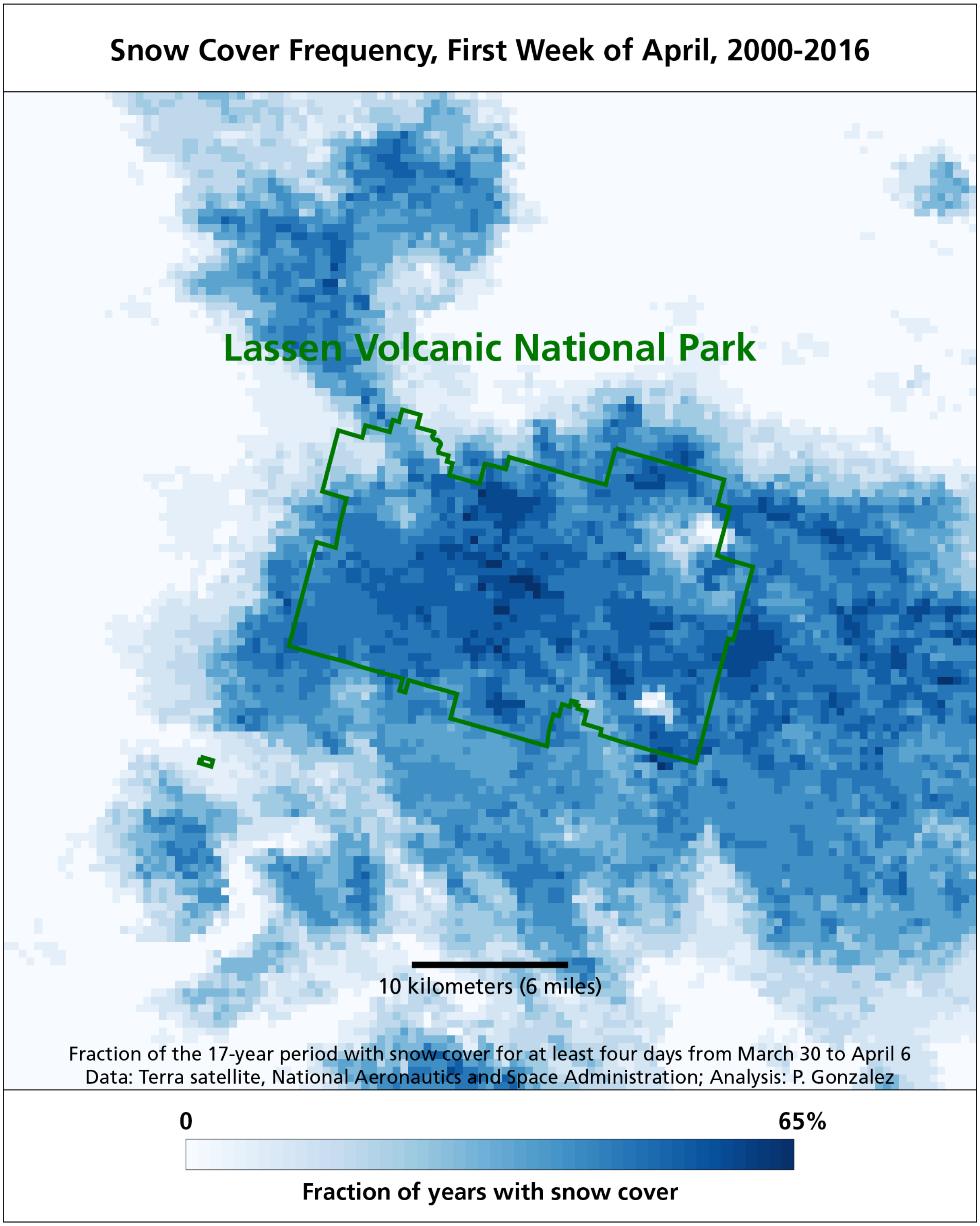
Main conclusion: Precipitation has decreased, but the rate has not been statistically significant.

Figure 5.



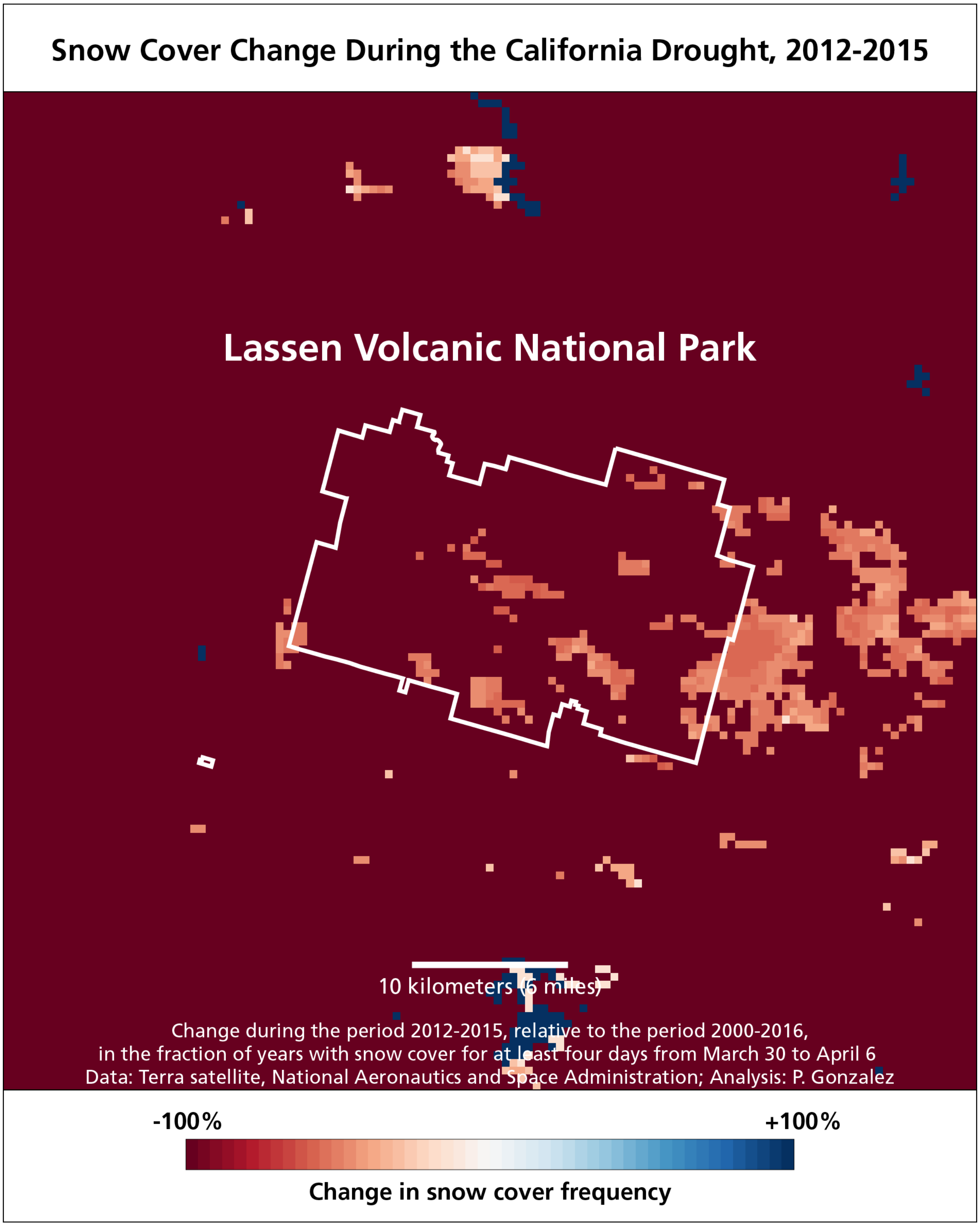
Main conclusion: Precipitation has decreased most in the Warner Valley and in the northwest section of the park.

Figure 6.



Main conclusion: Some areas of the park had snow cover in the early spring 11 out of 17 years.

Figure 7.



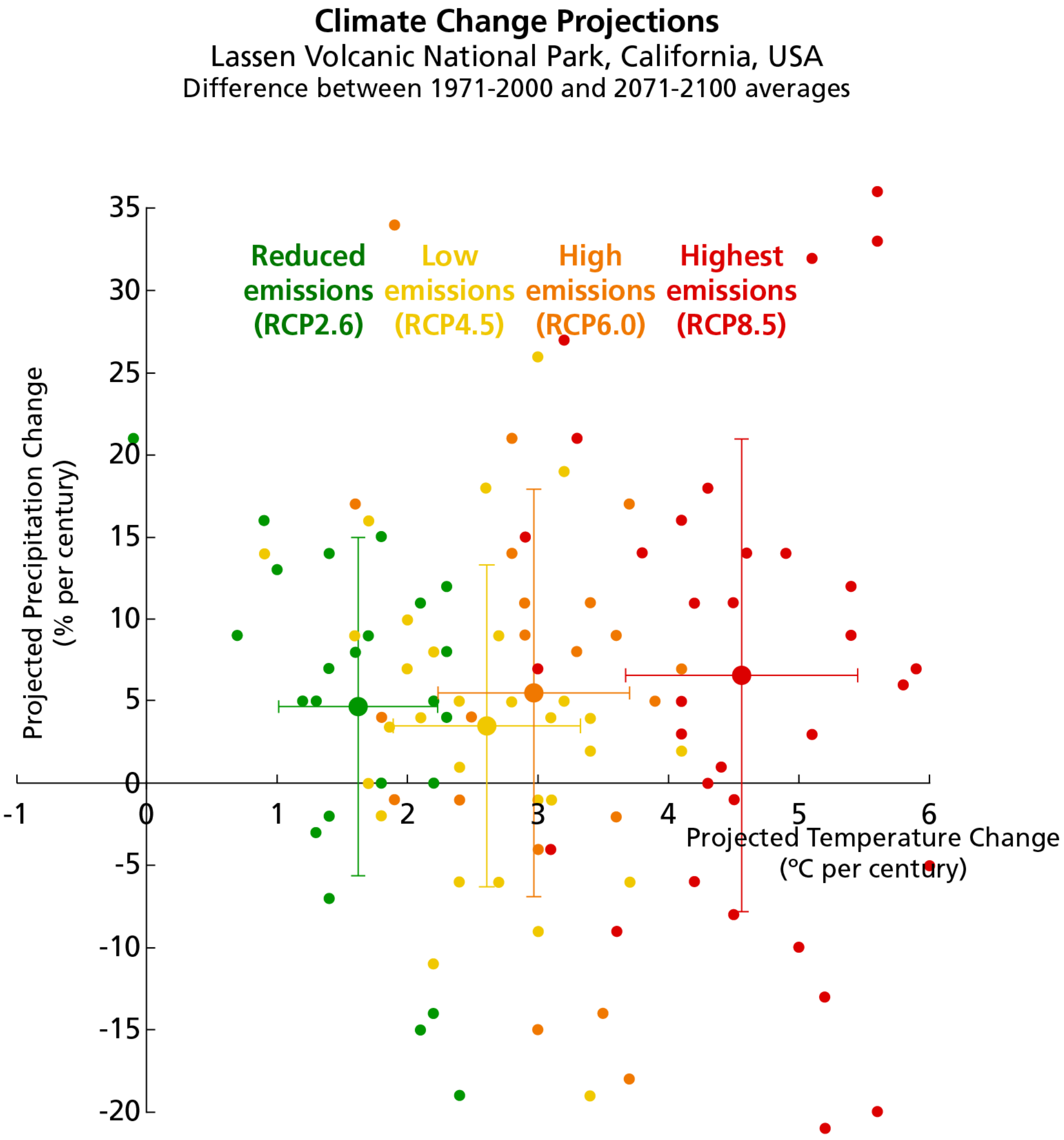
Snow Cover Change During the California Drought, 2012-2015

Change during the period 2012-2015, relative to the period 2000-2016, in the fraction of years with snow cover for at least four days from March 30 to April 6

Data: Terra satellite, National Aeronautics and Space Administration; Analysis: P. Gonzalez

Main conclusion: During the California Drought, snow cover completely disappeared by early spring across most of the park.

Figure 8.

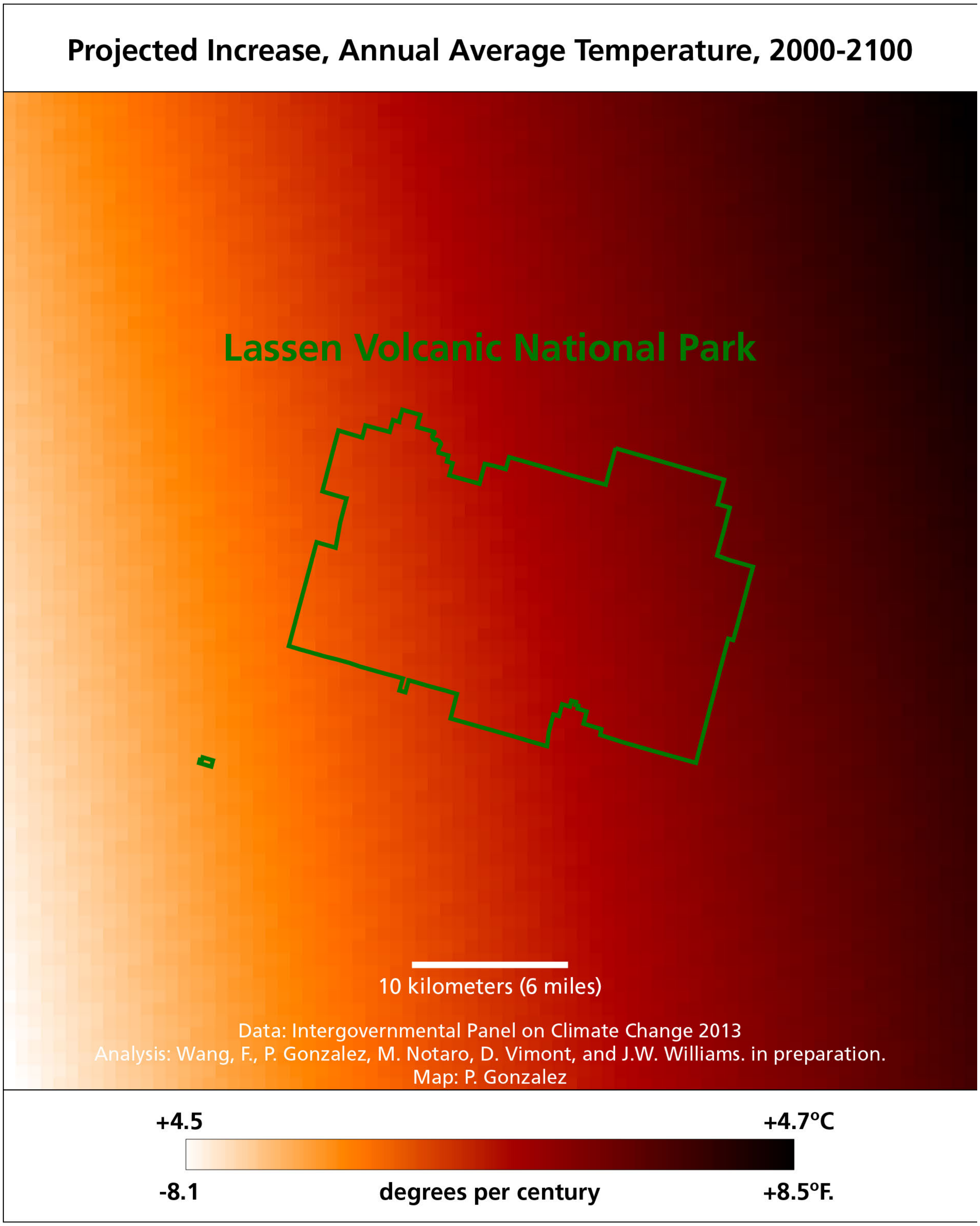


Data: Intergovernmental Panel on Climate Change 2013, Daly et al. 2008
Analysis: F. Wang, P. Gonzalez, M. Notaro, D. Vimont, J.W. Williams; Graph P. Gonzalez

Main conclusion: All models project increased temperature and two-thirds project increased precipitation.

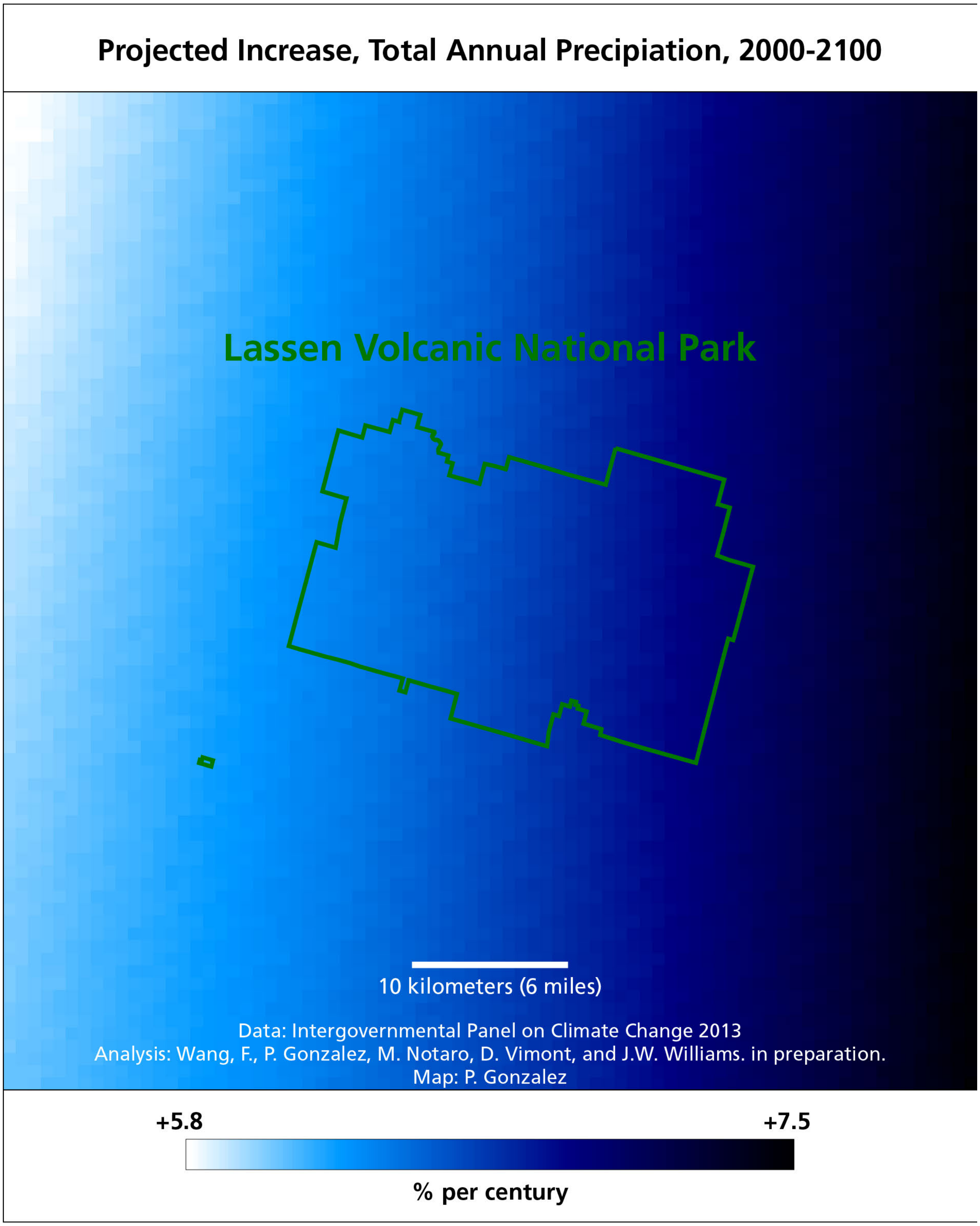
Projections of future climate for the area within park boundaries, relative to 1971-2000 average values. Each small dot is the output of a single GCM. The large color dots are the average values for the four IPCC emissions scenarios. The crosses are the standard deviations of each emissions scenario average. (Data: IPCC 2013, Daly et al. 2008; Analysis: F. Wang, P. Gonzalez, M. Notaro, D. Vimont, J.W. Williams).

Figure 9.



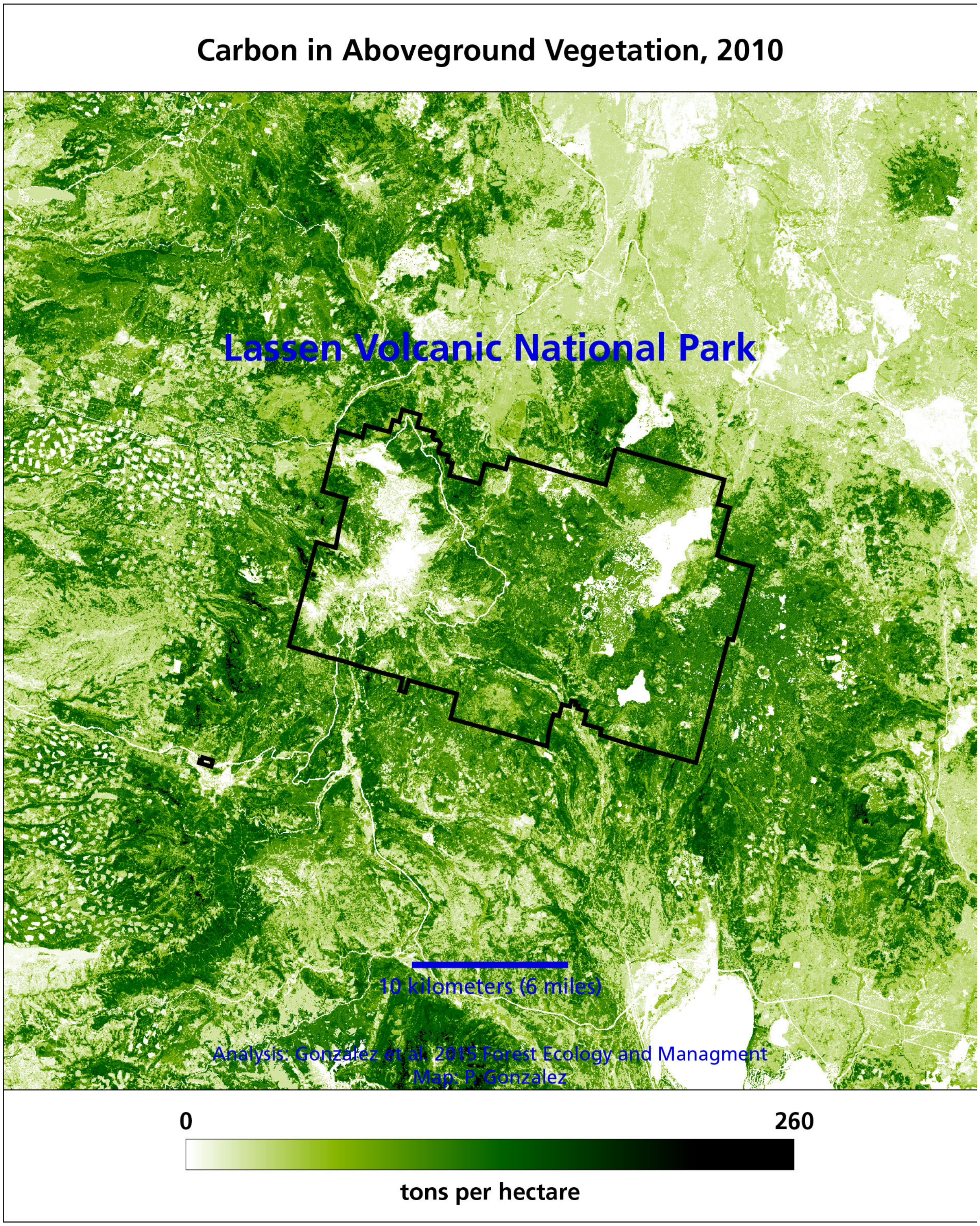
Main conclusion: Projected temperature changes are similar across the park.

Figure 10.



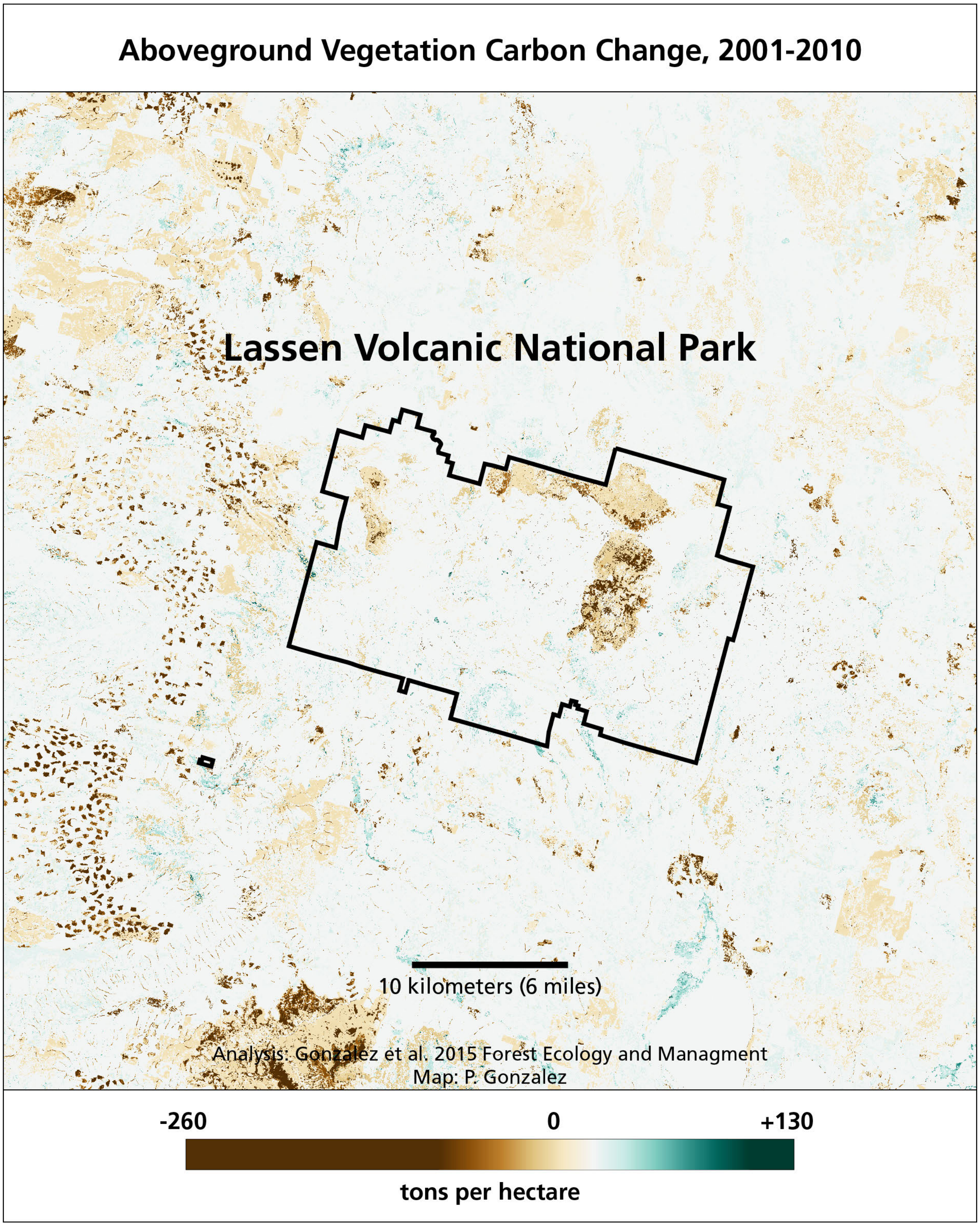
Main conclusion: Projected precipitation changes increase with distance from the Central Valley.

Figure 11.



Main conclusion: Carbon densities are highest in the mid-elevation forests.

Figure 12.



Main conclusion: Ecosystem carbon decreased in areas burned by wildfire.

Table 1. **Historical average temperatures** and temperature trends of the area within the boundaries of Lassen Volcanic N.P. SD = standard deviation, SE = standard error, sig. = statistical significance, * $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$.

	1971-2000		1895-2010			1950-2010		
	mean	SD	trend	SE	sig.	trend	SE	sig.
	ºC		ºC century^{-1}			ºC century^{-1}		
Annual	5.2	0.5	-0.2	0.2		-0.2	0.5	
December-February	-1.4	1.1	-0.2	0.3		0.6	0.8	
March-May	3	1.2	-0.2	0.3		1	0.7	
June-August	13.1	1	-0.3	0.4		-0.7	1.1	
September-November	6.1	1.2	-0.3	0.3		-1.4	1	
January	-1.6	1.4	0.5	0.5		3	1	**
February	-1	1.7	-0.2	0.5		0.5	1	
March	0	1.7	0.1	0.5		3.5	1	***
April	2.4	1.9	-0.9	0.5		-1	1.3	
May	6.5	1.8	0.2	0.5		0.4	1.1	
June	10.9	1.5	-0.1	0.5		-0.3	1.3	
July	14.5	1.4	-0.3	0.4		-0.9	1.4	
August	14	1.3	-0.5	0.4		-1	1	
September	11.2	1.7	0.4	0.5		-0.9	1.5	
October	6.4	1.7	-0.4	0.5		-1.6	1.3	
November	0.8	1.8	-1	0.4	*	-1.7	1.2	
December	-1.4	1.8	-0.8	0.5		-1.8	1.5	

Table 2. **Historical average precipitation** totals and precipitation trends of the area within the boundaries of Lassen Volcanic N.P. No trends were statistically significant.
SD = standard deviation, SE = standard error.

	1971-2000		1895-2010		1950-2010	
	mean	SD	trend	SE	trend	SE
	mm y^{-1}		% $century^{-1}$		% $century^{-1}$	
Annual	1737	587	-2	8	-11	22
December-February	807	373	0	13	-3	32
March-May	491	236	-4	12	20	30
June-August	79	44	9	20	-43	45
September-November	372	252	-7	18	-60	46
January	286	213	-23	22	-54	48
February	261	180	-4	18	26	48
March	239	167	-16	19	12	40
April	161	101	15	17	23	41
May	90	78	-9	23	34	55
June	40	34	-17	28	-36	61
July	13	13	49	35	-2	85
August	25	35	49	48	-75	122
September	41	43	-44	36	-84	102
October	113	87	-7	27	-55	69
November	219	203	-2	23	-59	62
December	249	200	27	21	22	58

Table 3. **Projected temperature increases** (°C), 2000 to 2050, for the area within Lassen Volcanic N.P. boundaries, from the average of all available general circulation model projections used for IPCC (2013). RCP = representative concentration pathway, SD = standard deviation.

	Emissions Scenarios							
	Reductions RCP2.6		Low RCP4.5		High RCP6.0		Highest RCP8.5	
	mean	SD	mean	SD	mean	SD	mean	SD
Annual	1.6	0.5	2	0.5	1.8	0.4	2.5	0.5
December-February	1.5	0.5	1.8	0.5	1.6	0.4	2.2	0.7
March-May	1.4	0.4	1.6	0.8	1.5	0.5	1.9	0.7
June-August	1.9	0.7	2.3	0.9	2	0.5	3	0.8
September-November	1.6	0.5	2.2	1.4	1.9	0.5	2.9	1.5
January	1.6	0.6	1.9	0.6	1.7	0.5	2.2	0.8
February	1.6	0.7	1.7	0.6	1.5	0.6	2	0.7
March	1.5	0.5	1.6	0.7	1.4	0.6	1.9	0.7
April	1.2	0.5	1.5	0.9	1.5	0.5	1.8	0.9
May	1.5	0.6	1.7	1.2	1.6	0.5	2.1	1
June	1.7	0.8	2	1.4	1.8	0.6	2.7	1.3
July	1.9	0.7	2.3	1.1	2.1	0.5	3	1.1
August	2	0.8	2.6	0.7	2.2	0.5	3.4	0.8
September	1.9	0.7	2.6	1.3	2.2	0.6	3.3	1.3
October	1.5	0.6	2.1	1.5	1.8	0.5	2.9	1.7
November	1.4	0.6	2	1.5	1.7	0.6	2.6	1.7
December	1.3	0.5	1.8	0.9	1.5	0.5	2.4	1.1

Table 4. **Projected temperature increases** (°C), 2000 to 2100, for the area within Lassen Volcanic N.P. boundaries, from the average of all available general circulation model projections used for IPCC (2013). RCP = representative concentration pathway, SD = standard deviation.

	Emissions Scenarios							
	Reductions RCP2.6		Low RCP4.5		High RCP6.0		Highest RCP8.5	
	mean	SD	mean	SD	mean	SD	mean	SD
Annual	1.6	0.6	2.6	0.7	3	0.7	4.6	0.9
December-February	1.6	0.6	2.3	0.7	2.6	0.7	4	0.9
March-May	1.4	0.6	2.1	0.9	2.5	0.6	3.7	1
June-August	1.7	0.8	3.1	1.1	3.6	0.9	5.5	1.1
September-November	1.7	0.7	3	1.6	3.2	0.9	5.2	1.8
January	1.8	0.7	2.4	0.8	2.7	0.8	4	1
February	1.6	0.7	2.2	0.8	2.7	0.8	3.9	1
March	1.5	0.7	2.1	0.8	2.5	0.7	3.6	1
April	1.4	0.6	1.9	0.9	2.4	0.6	3.5	1
May	1.4	0.7	2.3	1.1	2.7	0.8	4	1.3
June	1.6	1	2.7	1.5	3.2	1.1	4.9	1.6
July	1.7	0.8	3.1	1.4	3.7	1	5.5	1.4
August	1.8	0.9	3.4	1	3.8	1	6	1.1
September	2	0.9	3.4	1.5	3.7	1.1	5.9	1.7
October	1.6	0.8	2.9	1.8	3	0.9	5.2	2.1
November	1.5	0.6	2.6	1.7	2.8	0.9	4.4	2
December	1.6	0.5	2.4	1.1	2.5	0.8	4	1.3

Table 5. **Projected precipitation changes** (%), 2000 to 2050, for the area within Lassen Volcanic N.P. boundaries, from the average of all available general circulation model projections used for IPCC (2013). RCP = representative concentration pathway, SD = standard deviation.

	Emissions Scenarios							
	Reductions RCP2.6		Low RCP4.5		High RCP6.0		Highest RCP8.5	
	mean	SD	mean	SD	mean	SD	mean	SD
Annual	5	9	3	9	1	10	4	10
December-February	6	11	6	13	5	13	9	13
March-May	3	11	1	16	0	13	2	17
June-August	8	22	8	29	2	21	5	30
September-November	0	13	-4	23	-6	12	-8	20
January	11	17	9	18	9	19	12	18
February	4	18	4	18	1	22	8	20
March	5	16	1	18	4	17	7	24
April	2	17	2	21	-3	17	2	24
May	1	20	-3	27	-3	20	-7	23
June	3	24	-1	29	4	24	-3	31
July	23	48	30	67	20	40	17	59
August	19	58	23	53	-9	43	20	51
September	3	27	1	36	-11	32	-5	31
October	7	32	-1	34	-5	26	-9	31
November	-2	17	-5	27	-5	16	-7	23
December	7	24	9	24	8	23	12	19

Table 6. **Projected precipitation changes** (%), 2000 to 2100, for the area within Lassen Volcanic N.P. boundaries, from the average of all available general circulation model projections used for IPCC (2013). RCP = representative concentration pathway, SD = standard deviation.

	Emissions Scenarios							
	Reductions RCP2.6		Low RCP4.5		High RCP6.0		Highest RCP8.5	
	mean	SD	mean	SD	mean	SD	mean	SD
Annual	5	10	3	10	6	12	7	14
December-February	6	13	9	13	11	16	16	18
March-May	7	15	1	16	2	14	0	18
June-August	11	23	7	34	4	29	10	48
September-November	-2	13	-6	21	-3	17	-9	24
January	8	17	12	18	12	17	20	27
February	3	19	13	24	14	24	22	30
March	5	18	4	19	8	17	8	23
April	11	23	1	21	-3	22	-4	22
May	8	22	-7	22	-6	24	-12	26
June	6	26	-2	31	-1	30	-9	34
July	23	48	30	86	13	38	41	97
August	21	53	21	59	17	62	43	105
September	-3	32	0	29	2	26	7	50
October	8	33	-11	27	-4	37	-14	34
November	-5	12	-3	24	-3	17	-9	27
December	8	23	5	24	12	26	10	22

Table 7. **Ecosystem Carbon**. Aboveground carbon (mean ± 95% confidence interval) and surface area of changes in Lassen Volcanic N.P. (Gonzalez et al. 2015).

Carbon stock 2010	3.4 ± 2.1	million tons
Carbon density 2010	80 ± 50	tons ha^{-1}
Change 2001-2010	-0.23 ± 0.12	million tons
Change 2001-2010	-6 ± 3	% of amount
Carbon increase	4	% of area
Carbon decrease	15	% of area

References

Abatzoglou, J.T. and A.P. Williams. 2016. Impact of anthropogenic climate change on wildfire across western US forests. Proceedings of the National Academy of Sciences of the USA 113: 11 770-11 775.Adams 2010

Abatzoglou, J.T. and C.A. Kolden. 2011. Climate change in western US deserts: Potential for increased wildfire and invasive annual grasses. Rangeland Ecology and Management 64: 471-478.

Adams, R.A. 2010. Bat reproduction declines when conditions mimic climate change projections for western North America. Ecology 91: 2437-2445.

Adams, R.A. and M.A. Hayes. 2008. Water availability and successful lactation by bats as related to climate change in arid regions of western North America. Journal of Animal Ecology 77: 1115-121.

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.

Anacker, B.L., M. Gogol-Prokurat, K. Leidholm, and S. Schoenig. 2013. Climate change vulnerability assessment of rare plants in California. Madroño 60: 193-210.

Asner, G.P., P.G. Brodrick, C.B. Anderson, N. Vaughn, D.E. Knapp, and R.E. Martin. 2016. Progressive forest canopy water loss during the 2012–2015 California drought. Proceedings of the National Academy of Sciences of the USA 113: E249-E255.

Ault, T.R., A.K. Macalady, G.T. Pederson, J.L. Betancourt, and M.D. Schwartz. 2011. Northern Hemisphere modes of variability and the timing of spring in western North America. Journal of Climate 24: 4003-4014.

Barbour, M.G., N.H. Berg, T.G.F. Kittel, and M.E. Kunz. 1991. Snowpack and the distribution of a major vegetation ecotone in the Sierra Nevada of California. Journal of Biogeography 18: 141-49.

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: 1080-1083.

Beever, E.A., C. Ray, J.L. Wilkening, P.F. Brussard, and P.W. Mote. 2011. Contemporary climate change alters the pace and drivers of extinction. Global Change Biology 17: 2054-

2070.

Beever, E.A., J.D. Perrine, T. Rickman, M. Flores, J.P. Clark, C. Waters, S.S. Weber, B. Yardley, D. Thoma, T.C.-Preston, K.E. Goehring, M. Magnuson, N. Nordensten, M. Nelson, G.H. Collins. 2016. Pika (*Ochotona princeps*) losses from two isolated regions reflect temperature and water balance, but reflect habitat area in a mainland region. Journal of Mammalogy 97: 1495-1511.

Bentz, B.J., J. Régnière, C.J. Fettig, E.M. Hansen, J.L. Hayes, J.A. Hicke, R.G. Kelsey, J.F. Negrón, and S.J. Seybold. 2010. Climate change and bark beetles of the western United States and Canada: Direct and indirect effects. BioScience 60: 602-613.

Bonfils, C., B.D. Santer, D.W. Pierce, H.G. Hidalgo, G. Bala, T. Das, T.P. Barnett, D.R. Cayan, C. Doutriaux, A.W. Wood, A. Mirin, and T. Nozawa. 2008. Detection and attribution of temperature changes in the mountainous western United States. Journal of Climate 21: 6404-6424.

Boyte, S.P., B.K. Wylie, and D.J. Major. 2016. Cheatgrass percent cover change: Comparing recent estimates to climate change-driven predictions in the northern Great Basin. Rangeland Ecology and Management 69: 265-279.

Bradley, B.A., M. Oppenheimer, and D.S. Wilcove. 2009. Climate change and plant invasions: Restoration opportunities ahead? Global Change Biology 15: 1511-1521.

Buotte, P.C., J.A. Hicke, H.K. Preisler, J.T. Abatzoglou, K.F. Raffa, and J.A. Logan. 2017. Recent and future climate suitability for whitebark pine mortality from mountain pine beetles varies across the western US. Forest Ecology and Management 399: 132-142.

California Department of Fish and Wildlife. 2016. A Rapid Assessment of the Vulnerability of Sensitive Wildlife to Extreme Drought. California Department of Fish and Wildlife, Sacramento, CA.

Castillo, J.A., C.W. Epps, A.R. Davis, and S.A. Cushman. 2014, Landscape effects on gene flow for a climate-sensitive montane species, the American pika. Molecular Ecology 23: 843-856.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.

Clark, J.S., L. Iverson, C.W. Woodall, C.D. Allen, D.M. Bell, D.C. Bragg, A.W. D'Amato, F.W. Davis, M.H. Hersh, I. Ibanez, S.T. Jackson, S. Matthews, N. Pederson, M. Peters, M.W. Schwartz, K.M. Waring, and N.E. Zimmermann. 2016. The impacts of increasing drought on forest dynamics, structure, and biodiversity in the United States. Global Change Biology

22: 2329-2352.

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.

Curtis, J.A., L.E. Flint, A.L. Flint, J.D. Lundquist, B. Hudgens, E.E. Boydston, and J.K. Young. 2014. Incorporating cold-air pooling into downscaled climate models increases potential refugia for snow-dependent species within the Sierra Nevada Ecoregion, CA. PLoS One 9: e106984. doi:10.1371/journal.pone.0106984.

Daly, C., M. Halbleib, J.I. Smith, W.P. Gibson, M.K. Doggett, G.H. Taylor, J. Curtis, and P.P. Pasteris. 2008. Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. International Journal of Climatology 28: 2031-2064.

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 of the USA 112: 3931-3936.

Dolanc, C.R., R.D. Westfall, H.D. Safford, J.H. Thorne, and M.W. Schwartz. 2013. Growth–climate relationships for six subalpine tree species in a Mediterranean climate. Canadian Journal of Forest Research 43: 1114-1126.

Drexler, J.Z., D. Knifong, J. Tuil, L.E. Flint, and A.L. Flint. 2013. Fens as whole-ecosystem gauges of groundwater recharge under climate change. Journal of Hydrology 481: 22-34.

Dudley, R.W., G.A. Hodgkins, M.R. McHale, M.J. Kolian, and B. Renard. 2017. Trends in snowmelt-related streamflow timing in the conterminous United States. Journal of Hydrology 547: 208-221.

Dugger, K.M., E.D. Forsman, A.B. Franklin, R.J. Davis, G.C. White, C.J. Schwarz, K.P. Burnham, J.D. Nichols, J.E. Hines, C.B. Yackulic, P.F. Doherty, L. Bailey, D.A. Clark, S.H. Ackers, L.S. Andrews, B. Augustine, B.L. Biswell, J. Blakesley, P.C. Carlson, M.J. Clement, L.V. Diller, E.M. Glenn, A. Green, S.A. Gremel, D.R. Herter, J.M. Higley, J. Hobson, R.B. Horn, K.P. Huyvaert, C. McCafferty, T. McDonald, K. McDonnell, G.S. Olson, J.A. Reid, J. Rockweit, V. Ruiz, J. Saenz, and S.G. Sovern. 2016. The effects of habitat, climate, and barred owls on long-term demography of northern spotted owls. The Condor 118: 57-116.

Earles, J.M., M.P. North, and M.D. Hurteau. 2014. Wildfire and drought dynamics destabilize carbon stores of fire-suppressed forests. Ecological Applications, 24: 732-740.

Early, R., B.A. Bradley, J.S. Dukes, J.J. Lawler, J.D. Olden, D.M. Blumenthal, P. Gonzalez, E.D.

Grosholz, I. Ibañez, L.P. Miller, C.J.B. Sorte, and A.J. Tatem. 2016. Global threats from invasive alien species in the twenty-first century and national response capacities. Nature Communications 7: 12485. doi:10.1038/ncomms12485.

Eastman, L.M., T.L. Morelli, K.C. Rowe, C.J. Conroy, and C. Moritz. 2012. Size increase in high elevation ground squirrels over the last century. Global Change Biology 18: 1499-1508.

Eigenbrod, F., P. Gonzalez, J. Dash, and I. Steyl. 2015. Vulnerability of ecosystems to climate change moderated by habitat intactness. Global Change Biology 21: 275-286.

Flory, A.R., S. Kumar, T.J. Stohlgren, and P.M. Cryan. 2012. Environmental conditions associated with bat white-nose syndrome mortality in the north-eastern United States. Journal of Applied Ecology 49: 680-689.

Fyfe, J.C., C. Derksen, L. Mudryk, G.M. Flato, B.D. Santer, N.C. Swart, N.P. Molotch, X. Zhang, H. Wan, V.K. Arora, J. Scinocca, and Y. Jiao. 2017. Large near-term projected snowpack loss over the western United States. Nature Communications 8: 14996. doi: 10.1038/ncomms14996.

Gibson-Reinemer, D.K., K.S. Sheldon, and F.J. Rahel. 2015. Climate change creates rapid species turnover in montane communities. Ecology and Evolution 5: 2340-2347.

Gillies, K.E., P.J. Murphy, and M.D. Matocq. 2014. Hibernacula characteristics of Townsend's big-eared bats in Southeastern Idaho. Natural Areas Journal 34: 24-30.

Glenn, E.M., R.G. Anthony, E.D. Forsman, and G.S. Olson. 2011. Local weather, regional climate, and annual survival of the northern spotted owl. The Condor 113: 159-176.

Gonzalez, P. 2017. Climate change trends, impacts, and vulnerabilities in US national parks. In Beissinger, S.R., D.D. Ackerly, H. Doremus, and G.E. Machlis (eds.) Science, Conservation, and National Parks. University of Chicago Press, Chicago, IL.

Gonzalez, P., J.J. Battles, B.M. Collins, T. Robards, and D.S. Saah. 2015. Aboveground live carbon stock changes of California wildland ecosystems, 2001-2010. Forest Ecology and Management 348: 68-77.

Gonzalez, P., R.P. Neilson, J.M. Lenihan, and R.J. Drapek. 2010. Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change. Global Ecology and Biogeography 19: 755-768.

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

Hall, D.K., G.A. Riggs, and V.V. Salomonson. 2017. MODIS/Terra Snow Cover 8-day L3 Global 500m Grid V005. National Aeronautics and Space Administration, Greenbelt, MD.

http://nsidc.org/data/MOD10A2.

Hessburg, P.F., T.A. Spies, D.A. Perry, C.N. Skinner, A.H. Taylor, P.M. Brown, S.L. Stephens, A.J. Larson, D.J. Churchill, N.A. Povak, P.H. Singleton, B. McComb, W.J. Zielinski, B.M. Collins, R.B. Salter, J.J. Keane, J.F. Franklin, G. Riegel. 2016. Tamm Review: Management of mixed-severity fire regime forests in Oregon, Washington, and Northern California. Forest Ecology and Management 366: 221-250.

Hicke, J.A., A.J.H. Meddens, and C.A. Kolden. 2016. Recent tree mortality in the western United States from bark beetles and forest fires. Forest Science 62: 141-153.

Holt, A. 2009. Spatial analysis of plague in California: niche modeling predictions of the current distribution and potential response to climate change. International Journal of Health Geographics 8: 38.

Hurteau, M. and M. North. 2009. Fuel treatment effects on tree-based forest carbon storage and emissions under modeled wildfire scenarios. Frontiers in Ecology and the Environment 7: 409-414.

Hurteau, M.D. and M.L. Brooks. 2011. Short- and long-term effects of fire on carbon in US dry temperate forest systems. BioScience 61: 139-146.

Hurteau, M.D., J.B. Bradford, P.Z. Fulé, A.H. Taylor, and K.L. Martin. 2014. Climate change, fire management, and ecological services in the southwestern US. Forest Ecology and Management 327: 280-289.

Intergovernmental Panel on Climate Change (IPCC). 2013. Climate Change 2013: The Physical Science Basis. Cambridge University Press, Cambridge, UK.

Intergovernmental Panel on Climate Change (IPCC). 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Cambridge University Press, Cambridge, UK.

La Sorte, F.A. and F.R. Thompson. 2007. Poleward shifts in winter ranges of North American birds. Ecology 88: 1803-1812.

Langdon, J.G.R. and J.J. Lawler. 2015. Assessing the impacts of projected climate change on biodiversity in the protected areas of western North America. Ecosphere 6: 1-14.

Lauvaux, C.A., C.N. Skinner, and A.H. Taylor. 2016. High severity fire and mixed conifer forest-chaparral dynamics in the southern Cascade Range, USA. Forest ecology and management 363: 74-85.

Lebassi, B., J. González, D. Fabris, E. Maurer, N. Miller, C. Milesi, P. Switzer, and R. Bornstein. 2009. Observed 1970–2005 cooling of summer daytime temperatures in coastal California. Journal of Climate 22: 3558-3573.

Littell, J.S., D. McKenzie, D.L. Peterson, and A.L. Westerling. 2009. Climate and wildfire area burned in western U.S. ecoprovinces, 1916–2003. Ecological Applications 19: 1003-1021.

Loeb, S.C and E.A. Winters. 2013. Indiana bat summer maternity distribution: effects of current and future climates. Ecology and Evolution 3: 103-114.

Luo, L., D. Apps, S. Arcand, H. Xu, M. Pan, and M. Hoerling. 2017. Contribution of temperature and precipitation anomalies to the California drought during 2012–2015. Geophysical Research Letters 44: 3184–3192.

Lute, A.C., J.T. Abatzoglou, and K.C. Hegewisch. 2015. Projected changes in snowfall extremes and interannual variability of snowfall in the western United States. Water Resources Research 51: 960-972.

Lynch, A.J., B.J.E. Myers, C. Chu, L.A. Eby, J.A. Falke, R.P. Kovach, T.J. Krabbenhoft, T.J. Kwak, J. Lyons, C.P. Paukert, and J.E. Whitney. 2016. Climate change effects on North American inland fish populations and assemblages. Fisheries 41: 346-361.

Mann, M.L., E. Batllori, M.A. Moritz, E.K. Waller, P. Berck, A.L. Flint, L.E. Flint, and E. Dolfi. 2016. Incorporating anthropogenic influences into fire probability models: Effects of human activity and climate change on fire activity in California. PLoS ONE 11: e0153589. doi:10.1371/journal.pone.0153589.

Mao, Y., B. Nijssen, and D.P. Lettenmaier. 2015. Is climate change implicated in the 2013–2014 California drought? A hydrologic perspective. Geophysical Research Letters 42: 2805–2813.

Marlon, J.R., P.J. Bartlein, D.G. Gavin, C.J. Long, R.S. Anderson, C.E. Briles, K.J. Brown, D. Colombaroli, D.J. Hallett, M.J. Power, E.A. Scharf, and M.K. Walsh. 2012. Long-term perspective on wildfires in the western USA. Proceedings of the National Academy of Sciences of the USA 109: E535-E543.

Mathewson, P., L. Moyer-Horner, E.A. Beever, N.J. Briscoe, M. Kearney, J.M. Yahn, and W.P. Porter. 2016. Mechanistic variables can enhance predictive models of endotherm distributions: The American pika under current, past, and future climates. Global Change Biology: 1354-1013.

Mazer, S.J., K.L. Gerst, E.R. Matthews, and A. Evenden. 2015. Species-specific phenological responses to winter temperature and precipitation in a water-limited ecosystem. Ecosphere 6: 98. doi:10.1890/ES14-00433.1.

Meyer, G.A., J.A. Senulis, and J.A. Reinartz. 2016. Effects of temperature and availability of insect prey on bat emergence from hibernation in spring. Journal of Mammalogy 97: 1623-

1633.

Morelli, T.L., A.B. Smith, C.R. Kastely, I. Mastroserio, C. Moritz, and S.R. Beissinger. 2012. Anthropogenic refugia ameliorate the severe climate-related decline of a montane mammal along its trailing edge. Proceedings of the Royal Society of London B 279: 4279-4286.

Moritz, M.A., M.A. Parisien, E. Batllori, M.A. Krawchuk, J. Van Dorn, D.J. Ganz, and K. Hayhoe. 2012. Climate change and disruptions to global fire activity. Ecosphere 3: art49. doi:10.1890/ES11-00345.1.

Moss, R.H., J.A. Edmonds, K.A. Hibbard, M.R. Manning, S.K. Rose, D.P. van Vuuren, T.R. Carter, S. Emori, M. Kainuma, T. Kram, G.A. Meehl, J.F.B. Mitchell, N. Nakicenovic, K. Riahi, S.J. Smith, R.J. Stouffer, A.M. Thomson, J.P. Weyant, and T.J. Wilbanks. 2010. The next generation of scenarios for climate change research and assessment. Nature 463: 747-756.

National Park Service (NPS). 2017. NPSpecies, Park Species List, Lassen Volcanic National Park. https://irma.nps.gov/NPSpecies/Search/SpeciesList/LAVO.

National Park Service (NPS). 2011.Climate Friendly Parks. Lassen Volcanic Climate Action Plan. National Park Service, Washington, DC.

Paprocki, N., J.A. Heath, and S.J. Novak. 2014. Regional distribution shifts help explain local changes in wintering raptor abundance: Implications for interpreting population trends. PLOS One 9: e86814. doi:10.1371/journal.pone.0086814.

Pierce, D.W., T.P., Barnett, H.G. Hidalgo. T. Das, C. Bonfils, B.D. Santer, G. Bala, M.D. Dettinger, D.R. Cayan, A. Mirin, A.W. Wood, and T. Nozawa. 2008. Attribution of declining western U.S. snowpack to human effects. Journal of Climate 21: 6425-6444.

Pope, K., C. Brown, M. Hayes, G. Green, and D. Macfarlane. 2014. Cascades frog conservation assessment. General Technical Report PSW-GTR-244. U.S. Department of Agriculture, Forest Service, Albany, CA.

Raffa, K.F., B.H. Aukema, B.J. Bentz, A.L. Carroll, J.A. Hicke, M.G. Turner, and W.H. Romme. 2008. Cross-scale drivers of natural disturbances prone to anthropogenic amplification: The dynamics of bark beetle eruptions. BioScience 58: 501-517.

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, D.D. Ackerly, and S.R. Beissinger. 2014. Beyond a warming fingerprint: Individualistic biogeographic responses to heterogeneous climate change in California. Global Change Biology 20: 2841-2855.

Rehfeldt, G.E., N.L. Crookston, C. Sáenz-Romero, and E.M. Campbell. 2012. North American vegetation model for land-use planning in a changing climate: a solution to large classification problems. Ecological Applications 22: 119-141.

Rodhouse, T.J., E.A. Beever, L.K. Garrett, K.M. Irvine, M.R. Jeffress, M. Munts, and C. Ray. 2010. Distribution of American pikas in a low-elevation lava landscape: Conservation implications from the range periphery. Journal of Mammalogy 91: 1287-1299.

Rowe, K.C., K.M.C. Rowe, M.W. Tingley, M.S. Koo, J.L. Patton, C.J. Conroy, J.D. Perrine, S.R. Beissinger, and C. Moritz. 2015. Spatially heterogeneous impact of climate change on small mammals of montane California. Proceedings of the Royal Society of London B 282: 20141857. doi:10.1098/rspb.2014.1857.

Sandel, B. and E.M. Dangremond. 2012. Climate change and the invasion of California by grasses. Global Change Biology 18: 277-289.

Schwalm, D., C.W. Epps, T.J. Rodhouse, W.B. Monahan, J.A. Castillo, C. Ray, C. and M.R. Jeffress. 2016. Habitat availability and gene flow influence diverging local population trajectories under scenarios of climate change: a place-based approach. Global Change Biology 22: 1572-1584.

Seager, R., M. Hoerling, S. Schubert, H. Wang, B. Lyon, A. Kumar, J. Nakamura, and N. Henderson. 2015. Causes of the 2011–14 California Drought. Journal of Climate 28: 6997–7024

Shukla, S., M. Safeeq, A. AghaKouchak, K. Guan, and C. Funk. 2015. Temperature impacts on the water year 2014 drought in California. Geophysical Research Letters 42: 4384–4393.

Stephens, S.L. and L.W. Ruth. 2005. Federal forest-fire policy in the United States. Ecological Applications 15: 532-542.

Stephens, S.L., J.K. Agee, P.Z. Fulé, M.P. North, W.H. Romme, T.W. Swetnam, and M.G. Turner. 2013. Managing forests and fire in changing climates. Science 342: 41-42.

Stephens, S.L., R.E. Martin, and N.E. Clinton. 2007. Prehistoric fire area and emissions from California's forests, woodlands, shrublands, and grasslands. Forest Ecology and Management 251: 205-216.

Stewart, J.A.E., J.D. Perrine, L.B. Nichols, J.H. Thorne, C.I. Millar, K.E. Goehring, C.P. Massing, and D.H. Wright. 2015. Revisiting the past to foretell the future: Summer temperature and habitat area predict pika extirpations in California. Journal of Biogeography 42: 880-890.

Sturrock, R.N., S.J. Frankel, A.V. Brown, P.E. Hennon, J.T. Kliejunas, K.J. Lewis, J.J. Worrall, and A.J. Woods. 2011. Climate change and forest diseases. Plant Pathology 60: 133-149.

Taylor, A.H. 1995. Forest expansion and climate-change in the mountain hemlock (*Tsuga mertensiana*) zone, Lassen Volcanic National Park, California, USA. Arctic and Alpine Research 27: 207-216.

Taylor, A.H. 2000. Fire regimes and forest changes in mid and upper montane forests of the southern Cascades, Lassen Volcanic National Park, California, U.S.A. Journal of Biogeography 27: 87-104.

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 6:24. doi:10.1890/ES14-00300.1.

Tingley, M.W., M.S. Koo, C. Moritz, A.C. Rush, and S.R. Beissinger. 2012. The push and pull of climate change causes heterogeneous shifts in avian elevational ranges. Global Change Biology 18: 3279-3290.

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 of the United States of America 106: 19 637-19 643.

Trouet, V., A.H. Taylor, E.R. Wahl, C.N. Skinner, and S.L. Stephens. 2010. Fire-climate interactions in the American West since 1400 CE. Geophysical Research Letters 37: L04702. doi:10.1029/2009GL041695.

van Mantgem, P.J., N.L. Stephenson, J.C. Byrne, L.D. Daniels, J.F. Franklin, P.Z. Fule, M.E. Harmon, A.J. Larson, J.M. Smith, A.H. Taylor, and T.T. Veblen. 2009. Widespread increase of tree mortality rates in the western United States. Science 323: 521-524.

Van Martin, M., C.L. Heald, J.F. Lamarque, S. Tilmes, L.K. Emmons, and B.A. Schichtel. 2015. How emissions, climate, and land use change will impact mid-century air quality over the United States: A Focus on effects at national parks. Atmospheric Chemistry and Physics 15: 2805-2823.

Varner, J., J.J. Horns, M.S. Lambert, E. Westberg, J.S. Ruff, K. Wolfenberger, E.A. Beever, and M.D. Dearing. 2016. Plastic pikas: Behavioural flexibility in low-elevation pikas (*Ochotona princeps*). Behavioural Processes 125: 63-71.

Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, and J. Willis. 2014. Our changing climate. In Melillo, J.M., T.C. Richmond, and G. W. Yohe (Eds.) Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, Washington, DC.

Wang, F., P. Gonzalez, M. Notaro, D. Vimont, and J.W. Williams. in preparation. Significant historical and projected climate change in U.S. national parks.

Wenger, S.J., D.J. Isaak, C.H. Luce, H.M. Neville, K.D. Fausch, J.B. Dunham, D.C. Dauwalter, M.K. Young, M.M. Elsner, B.E. Rieman, A.F. Hamlet, and J.E. Williams. 2011. Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. Proceedings of the National Academy of Sciences of the USA 108: 14 175-14 180.

Westerling, A.L. 2016. Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. Philosophical Transactions of the Royal Society B 371: 20150178. doi:10.1098/rstb.2015.0178.

Westerling, A.L., B.P. Bryant, H.K. Preisler, T.P. Holmes, H.G. Hidalgo, T. Das, and S.R. Shrestha. 2011. Climate change and growth scenarios for California wildfire. Climatic Change 109: S445-463.

Wilkening, J.L., C. Ray, and J. Varner. 2016. When can we measure stress noninvasively? Postdeposition effects on a fecal stress metric confound a multiregional assessment. Ecology and Evolution 6: 502-513.

Williams, A.P., R. Seager, J.T. Abatzoglou, B.I. Cook, J.E. Smerdon, and E.R. Cook. 2015. Contribution of anthropogenic warming to California drought during 2012–2014. Geophysical Research Letters 42: 6819-6828.

Wolf, A., N.B. Zimmerman, W.R.L. Anderegg, P.E. Busby, and J. Christensen. 2016. Altitudinal shifts of the native and introduced flora of California in the context of 20th-century warming. Global Ecology and Biogeography 25: 418-429.

Wood, A.W., L.R. Leung, V. Sridhar and D.P. Lettenmaier. 2004. Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs. Climatic Change 62: 189-216.