Rausser College of Natural Resources
University of California, Berkeley

The Three Sisters trees (giant sequoia (*Sequoiadendron giganteum*)) in Sequioa National Park (photo Dr. Anthony Ambrose).

Anthropogenic Climate Change in Sequoia and Kings Canyon National Parks, California, USA

Kathryn Low

University of California, Berkeley
Department of Environmental Science, Policy, and Management

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Abstract

Greenhouse gas emissions from the human enterprise have caused anthropogenic climate change, which affects both natural and human systems. This report aims to assess existing research concerning historical climate change impacts and trends within Sequoia and Kings Canyon National Parks, future risks, and viable ecosystem management strategies to conserve park resources in the context of an uncertain future. Average annual temperatures exhibited a statistically significant increase ($p < 0.001$) of 0.9℃±0.2℃ per century from 1885 to 2017 within the boundary of Sequoia and a statistically significant increase ($p=0.0007$) of 0.7℃±0.2℃ per century from 1885-2017 within the boundary of Kings Canyon. Recent regional research, some of which includes data from the parks, has identified several statistically significant changes attributed to anthropogenic climate change, including significant declines in snowpack in the western US, a doubling of tree mortality rates in mid-elevation, old growth Sierran mixed-conifer forests from 1983 to 2007, and a doubling of the area burned by wildfire relative to natural levels from 1984 to 2015. Under the highest greenhouse gas emissions scenario of the Intergovernmental Panel on Climate Change (Representative Concentration Pathway (RCP) 8.5), thirty-three climate models project average annual temperatures increasing 4.7℃±0.9℃ and 4.8℃±1.0℃ by 2100 in Sequoia and Kings Canyon respectively. Reducing human sources of emissions (RCP 2.6) could reduce projected warming by two-thirds in both parks. Although precipitation projections remain highly variable, under RCP 8.5, the probability of a severe statewide drought by 2030 increases to nearly 100%. Research has also projected several future risks to park ecosystems and resources including an increased risk of tree mortality from drought by 15-20% per degree Celsius increase in the Sierra Nevada, an increase in the number of extreme fire weather days in the state of one- to two-thirds by 2050, and increases of the peak streamflow of three major river systems in both parks of up to four times in the coming decades. There are key adaptation options managers can implement to reduce the future risks of climate change such as implementing fuels reduction treatments (e.g. prescribed fire and hand thinning), planting sequoia seed stock more likely adapted to future conditions in areas with projected future suitable habitat, and establishing habitat corridors to assist elevational and latitudinal migrations of species. Sequoia forests in the parks store up to 1400 Mg C/ha; applying fuels treatments can significantly stabilize live tree carbon stocks. In 2006, transportation of visitors and staff generated 66% of the 2700 tons/year of carbon of park emissions. Reducing park vehicle fleet size, designing more extensive public transportation

systems through the parks, limiting energy consumption in all facilities, and reducing waste produced by park operations can reduce fossil fuel consumption and park emissions.

Introduction

Greenhouse gas emissions from the human enterprise have caused climate change (IPCC 2013). Globally, anthropogenic climate change affects both natural and human systems through sea level rise, extinctions of animals, more frequent wildfires, altering of ecosystem services, and other effects (IPCC 2014; IPCC 2018). Climate change continues to affect communities and ecosystems in the United States (USGCRP 2017), including the areas designated as National Parks (Gonzalez 2017; Gonzalez et al. 2018).

Recognizing the seriousness of projected climate change risks to park resources, national park researchers and managers are devising park-specific resource management plans to minimize climate change-caused ecosystem degradation. This report aims to assess existing research concerning historic climate change impacts and trends within Sequoia and Kings Canyon National Parks, future risks, and viable ecosystem management strategies to conserve park resources in the context of an uncertain future.

Location Description

Sequoia and Kings Canyon National Parks (SEKI) are contiguous parks located on the western slope of the southern Sierra Nevada mountain range in California, USA. The parks are a combined 350,443 hectares (865,964 acres) (Figure 1), with approximately 97% of managed area designated as wilderness (NPS 2013). Both parks span an extensive vertical relief from the low foothills to the crest of the Sierra (418-4420 m) with Sequoia including Mount Whitney, the highest point (4420 m) in the lower 48 states. Four major watersheds originate from the parks: (1) San Joaquin, (2) Kings, (3) Kern, and (4) Kaweah. Other prominent features include numerous caves, lakes, ponds, glaciers, and montane meadows.

The parks contain four major ecological zones (Figure 2). Low elevation hardwoods and chaparral contains plant communities adapted to Mediterranean climates. Montane is the largest zone by area (Figure 2) containing mixed-conifer forests and 37 giant sequoia

(*Sequoiadendron giganteum* (Lindl.) Buchholz) groves, which contain four of the largest trees by volume on earth (NPS 2013). The subalpine and alpine zones contain alpine ridges and subalpine forests. There are 299 native vertebrate species that reside in both parks; currently, 54 animal species that reside within park boundaries are listed as threatened or endangered by federal and/or state resource departments. There are also 1,442 species of vascular plants within park boundaries, of which 102 are endemic to the Sierra Nevada ecoregion and nine are locally endemic (found within 8 km of park boundaries) (NPS 2013).

Historical Climate Trends

Temperature Average annual temperatures exhibited statistically significant trends ($p < 0.001$) of 0.9℃±0.2℃ per century from 1895 to 2017 within the boundary of Sequoia and a statistically significant change ($p=0.0007$) of 0.7℃±0.2℃ per century from 1895 to 2017 within the boundary of Kings Canyon (Figure 3; Gonzalez et al. 2018). When comparing records from five weather stations within or near the parks, Das and Stephenson (2013) found that average temperatures increased by 0.58℃ from 1975 to 2011, which is approximately 0.35℃ per decade.

Rates of warming were highest during the spring and summer (Table 1, Table 2; Gonzalez et al. 2018). Spatially, the greatest increases in temperature from 1895 to 2016 were in the southern end of Sequoia (Figure 4, Gonzalez et al. 2018). Heightened warming was observed at all elevations in the region, with some data indicating higher elevations are warming faster (Figure 5; Das and Stephenson 2013). Additionally, Meyer and Safford (2010) report a decrease in the occurrence of nighttime freezing temperatures over the last century in the southern Sierra Nevada.

Precipitation Average annual precipitation did not exhibit statistically significant trends from 1895 to 2017 within the boundaries of both Kings Canyon and Sequoia (Figure 6; Gonzalez et a. 2018). Total precipitation within park boundaries continues to have high annual variability but does not exhibit significant trends over time (Figure 6; Figure 8; Das and Stephenson 2013; Gonzalez et al. 2018).

Spatially, the greater decreases in total annual precipitation from 1895 to 2017 occurred in the northwest area of Sequoia and southwest area of Kings Canyon (Figure 7; Gonzalez et al.

2018). Higher elevations in the southern Sierra are experiencing moderate increases in precipitation, while lower elevations have seen decreases in precipitation (Meyer and Safford 2010). Rice and Bales (2013) reported statistically significant ($p<0.001$) declines in regional snowpack at elevations below 2590 m but increases at elevations greater than 2590 m.

Drought California's 2012-2016 drought was the most severe drought in the last century and perhaps in the last 1200 years (Griffin and Anchukaitis 2014; Diffenbaugh et al. 2015; Williams et al. 2015; Lund et al. 2018). Near-surface soil moisture in 2014 had the lowest recorded Palmer Drought Severity Index (PDSI) in the period between 1895-2017 (www.ncdc.noaa.gov/cag/; Williams et al. 2015). Regional PDSI analyses indicated that soil moisture deficits for the Sierra Nevada were more severe relative to values calculated for the state as a whole (Williams et al. 2015). In the southern Sierra Nevada, drought intensity was likely due to decreased snowpack at higher elevations (Mote 2006) and subsequent reductions in spring and summer melt-driven soil moisture inputs (Williams et al. 2015).

Anthropogenic-caused warming has led to a statistically significant increase in the risk of events with extremely-low precipitation in California (Diffenbaugh et al. 2015). Warming also was the primary contributor to high calculated evapotranspiration values during the height of the drought (Diffenbaugh et al. 2015). Williams et al. (2015) reports that regional warming caused by anthropogenic climate change was responsible for 8-27% of the severity of the California drought from 2012 to 2014.

Historical Impacts

Detected regional changes attributed to anthropogenic climate change

Research conducted in the western US identify several changes that are statistically significant from historical trends, and caused, in part, by anthropogenic climate change.

Reductions in snowpack and glacial area Climate change has led to significant ($p < 0.05$) declines in snowpack across the western US from 1959-1990 (Pierce et al. 2008). Globally, anthropogenic climate change has caused two-thirds of glacial melting since 1991 (Marzeion et al. 2014). Increases in spring temperatures attributed to human-caused climate change (IPCC 2013) have resulted in an average 55% loss of glacial area over the past 100 years in national parks in the Sierra Nevada region (Basagic and Panek 2013).

Altered quantity and timing of montane streamflows In the southern Sierra, reductions in snowpack attributed to climate change have led to subsequent decreases in peak flows of major river systems from 1950 to 1999 (Barnett et al. 2008). Hidalgo et al. (2009) also report significant ($p < 0.05$) advances in peak flows in montane rivers in the western US during the winter and spring from 1950-1999 due to anthropogenic climate change.

Extensive bark beetle outbreaks Increases in temperatures attributed to climate change influenced the magnitude and extent of the most recent bark beetle outbreak in western North America through providing ideal climate conditions for the various life history stages for beetles (Raffa et al. 2008; Bentz et al. 2010). Climate change-induced bark beetle outbreaks have caused trace amounts of mortality in 5% of forest area in the western US (Macfarlane et al. 2013). However, observed beetled-caused mortality of 30-60% in regions of western North America, including southern Sierra Nevada, is also common (Hicke et al. 2012).

Heightened mixed-conifer mortality Rising temperatures and prolonged drought stress caused by anthropogenic climate change have doubled mortality rates of mid-elevation, old growth Sierran mixed-conifer forests from 1983 to 2007 (van Mantgem et al. 2009).

Increases in wildfire size and frequency Wildfires in giant sequoia groves in the Sierra, including those in both parks, were correlated with decadal-to-centennial variations in temperature from 1000 to 1860 A.D., after which time, active fire suppression caused a rift between observed and potential fires (Swetnam 1993). In the western US, anthropogenic climate change has caused over half of the increases in fuel aridity from 1979 to 2015 and has doubled the area burned by wildfire relative to natural levels from 1984 to 2015 (Abatzoglou and Williams 2016). Climate change has also lengthened the wildfire season in the western US (Jolly et al. 2015).

Species mammal range shifts When comparing surveys of small mammals in the Sierra from both Joseph Grinnell (1914-1920) and UC Berkeley's Museum of Vertebrate Zoology's more recent resurveys, Mortiz et al. (2008) concluded that elevation limits of geographic ranges shifted upward and several high-elevation species showed range contractions. Range shifts for high-elevation species were caused by the temperature increases of anthropogenic climate change, not by land use change, since the high-elevation plots were in Yosemite National Park and protected, however changes in ranges of low- to mid-elevation species were driven by local land management (Moritz et al. 2008).

Decline of bumblebee populations The increased temperatures of anthropogenic climate change have led to the rapid and extensive decline of bumble bee (*Bombus*) species by 46% ± 3.3% in North America, relative to species distributions from 1901-1974 (Soroye et al. 2020). Species occupancy was negatively correlated with increases in temperature that exceed species' upper thermal limits and in sites that have become drier (Soroye et al. 2020).

Changes in bird species distributions Anthropogenic climate change has shifted the winter ranges of birds northward 30 km across the US from 1975 to 2004 (La Sorte and Thompson 2007). Increases in winter temperatures attributed to climate change have shifted wintering locations for raptor species across western North America from 1975 to 2011 (Paprocki et al. 2014). Golden eagles (*Aquila chrysaetos* (Linnaeus)), which are known to inhabit both parks, exhibited a significant ($p < 0.0001$) rate of range shift, moving northward 8 km per year (Paprocki et al. 2014).

Regional changes that are consistent with but not formally attributed to anthropogenic climate change

Additional research conducted in California document changes consistent with anthropogenic climate change. Findings either did not report statistically significant changes relative to reference conditions or did not formally incorporate climate attribution into their analyses.

Recent mixed-conifer mortality and decline in health of mature giant sequoia More than 100 million trees died statewide in response to a combination of the 2012-2016 drought and recent bark beetle outbreak, which were both attributed to climate change (USDA Forest Service 2016; Young et al. 2017). During the 2012-2016 drought, sequoia groves in the region experienced significant declines in grove wetness (an average loss of 25% in groves and > 50% in background areas relative to levels from 1985 to 2010) due to a combination of climate-caused increases in temperatures and drought severity (Su et al.

2017). Although less than 1% of the 5000 mature sequoia in both parks succumbed to drought mortality, many experienced unprecedented levels of drought-induced foliage dieback (some > 50%) (Stephenson et al. 2018).

Increase in wildfire size in the Sierra Nevada Climate-induced increases in temperature and variability in spring precipitation have led to a 35-50% increase in average and maximum fire size in the Sierra from 1980-2007 (Miller et al. 2009).

Future Climate Projections

Temperature Thirty-three climate models project that under the highest emissions scenario (RCP 8.5), mean annual temperatures of the area within Sequoia would increase 4.7℃±0.9℃ by 2100 (Figure 9, Table 5; Gonzalez et al. 2018) compared to the 1971-2000 reference period. Mean annual temperatures of the area within Kings Canyon are projected to increase 4.8℃±1.0℃ by 2100 (Table 6) under RCP 8.5 compared to the 1971-2000 reference period (IPCC 2013; Gonzalez et al. 2018). Reducing anthropogenic greenhouse gas emissions (RCP 2.6) could reduce projected warming by nearly two-thirds in both parks (1.6℃±0.7℃ in Sequoia and 1.7℃±0.8℃ in Kings Canyon by 2100) (Gonzalez et al. 2018). Projections indicate that greater increases in temperature may occur from September to November in both parks (Table 5, Table 6; Gonzalez et al. 2018).

Precipitation In both Sequoia and Kings Canyon, models project insignificant increases in annual precipitation across emissions scenarios (Table 7, Table 8; Gonzalez et al. 2018). Models project increases in winter and summer precipitation and decreases in spring and fall precipitation from 2000 to 2100 under RCPs 4.5, 6.0 and 8.5 (Table 7, Table 8; Gonzalez et al. 2018). Potential increases in precipitation in the parks may be overshadowed by expected drier conditions due to warming causing greater rates of evaporation and evapotranspiration (Thorne et al. 2015; Su et al. 2017). Additionally, anthropogenic climate change may increase extreme dry-to-wet precipitation events 25-100% in California, despite moderate changes in average annual precipitation (Swain et al. 2018).

Projections indicate regional snowpack may gradually reduce at lower elevations and decrease at greater rates at higher elevations (Liu et al. 2020). Towards the end of the century, snowpack could be significantly reduced by approximately 50-100 mm in the Kaweah watershed and by approximately 100 mm in the western, lower-elevation region of the Kings watershed (Liu et al. 2020). Under RCP 4.5, snowpack is projected to moderately increase in the High Sierra by up to 70 mm relative to levels from 2004 to 2013 (Liu et al. 2020). Elevation-related results are consistent with statewide projections that snowpack may decrease 22-93% at elevations below 3000 m by 2100, under all emissions scenarios (Hayhoe et al. 2004). By 2100 under the highest emissions scenario, regional snowpack at low elevations may completely disappear and could diminish at increasingly greater rates in the high-elevation regions of the Kings and Kern watersheds (Liu et al. 2020).

Drought Rising temperatures attributed to climate change have increased the likelihood of drought events in California due to simultaneous increases in probabilities of greater temperatures and low-precipitation events (Diffenbaugh et al. 2015). Under RCP 8.5, projected warming attributed to anthropogenic climate change has also increased the occurrence of severe drought conditions (i.e. extremely warm annual-scale dry periods) by nearly 100% by 2030 in California (Diffenbaugh et al. 2015). Additionally, climatic water deficits in the Sierra Nevada are projected to increase, especially in the summer (Thorne et al. 2015). Across the southwestern US, including the southern Sierra, models project that under RCP 8.5, climate change also increases the likelihood of a mega-drought more severe than others observed in the last 1000 years by 2100 (Cook et al. 2015).

Future Risks

In the absence of reductions of greenhouse gas emissions from the human enterprise, anthropogenic climate change may increase vulnerabilities of ecosystems and species to mortality and other adverse effects (IPCC 2013; IPCC 2014). Research conducted both in Sequoia and Kings Canyon and the surrounding region highlights multiple potential climate change risks to vegetation and wildlife.

Montane Hydrology

Increases in peak streamflow Regional rises in temperature from climate change are projected to increase peak streamflow of three major river systems (Kings, Kern, and Kaweah) in both parks up to four times in magnitude in the coming decades (Liu et al. 2020). Average monthly streamflow is projected to increase from October to March in the southern Sierra's major watersheds as soon as by 2100 (Liu et al. 2020). Earlier snowmelt due to climate change could lead to regional peak streamflows arriving 2 to 4 months earlier in the year (Liu et al. 2020).

Greater frequencies in flood events Under the highest emissions scenario (RCP 8.5), extreme flows of river systems within the parks and the region are projected to become more severe by the end of the century (Liu et al. 2020). Regional watersheds could reach flooding conditions more frequently in the future (Liu et al. 2020). Climate change could increase the magnitude of severe storms, increasing the severity of floods in regions of California with more rain-on-snow events or more intense snowmelt (Das et al. 2011; Liu et al. 2020). The frequency of fifty-year floods in the state increases 50-100% by 2100 under the highest emissions scenario (Das et al. 2011).

Vegetation

Challenges to sequoia grove health and species range If projected increases in temperature and frequencies of drought in the Sierra Nevada are realized, giant sequoias may be at risk for climate change-driven shifts in available moisture (Safford et al. 2012b). Giant sequoia have historically been considered to be highly resistant to forest disturbances relative to other species (Hartesveldt et al. 1975; Piirto 1994). However, sequoias possess traits that suggest future vulnerability to climate change: requiring large amounts of water (> 2000 L per summer day) (Ambrose et al. 2016) and relatively low genetic diversity (Fins and Libby 1994; Dodd and DeSilva 2016). Based on significant correlations between normalized difference vegetation indices (NDVI) and evapotranspiration in the western Sierra over the last 30 years, Su et al. (2017) projects an 70-80 mm/yr rise in regional annual evapotranspiration, which corresponds to 800 mm/yr of total annual evapotranspiration in sequoia groves. However, not all mature sequoias will experience the same environmental stressors; Nydick et al. (2018) observed significant stress levels in some mature trees within park boundaries during the 2012-2016 drought while others were seemingly unaffected. Because sequoia groves have greater water availability than the surrounding forest, they may serve as hydrologic refugia for many species (Rundel 1972; McLaughlin et al. 2017; Su et al. 2017).

Increased risk of mixed-conifer forest mortality Projected frequencies in extreme weather events may increase the frequency and magnitude of severe ecological disturbances in the Sierra, driving rapid and persistent landscape-level changes in forest composition, function and structure (Fettig et al. 2019). Climate change may increase the risk of tree mortality from drought by 15-20% per degree Celsius increase in the Sierra Nevada through projected increases of evapotranspiration and soil moisture overdraft during drought events (Goulden and Bales 2019). Under high emissions scenarios, climate change may increase risk of tree mortality up to 50% in conifer-dominated forests in the southwestern US (McDowell et al. 2016; Buotte et al. 2019; Goulden and Bales 2019).

Increases in suitable habitat and range expansion for invasive species Projections suggest that in California, forest types and other vegetation dominated by woody plants may migrate to higher elevations as warmer temperatures make those areas suitable for colonization and survival (Lenihan et al. 2003;2008). Under a 3℃ rise in temperature, habitat conditions in both parks are projected to be highly favorable for Italian thistle (*Carduus pycnocephalus* (Bossard and Lichti)), an invasive plant, and Himalayan blackberry (*Rubus armeniacus* (Focke)) (NPS 2013). In the twenty-first century, climate-driven biome shifts and changes in fire frequency are likely to increase invasion threats of invasive species in California (Early et al. 2016).

Increases in wildfire frequency and severity In California, climate change has increased the probability of large fall wildfires; this effect may increase in the coming decades (Williams et al. 2019). Climate change may increase the number of extreme fire weather days in the state one- to two-thirds by 2050 (Williams et al. 2019; Goss et al. 2020). Under the highest emissions scenario, climate change could quadruple the number of average annual hectares burned in the Sierra by 2100 (Westerling et al. 2018). The scale of present tree mortality, particularly in the southern Sierra Nevada, is so large that there is greater potential for “mass fire,” or fire events where large areas burn simultaneously, in the coming decades, as the likelihood of severe fires is influenced by unprecedented volumes of continuous dry, combustible fuels (Stephens et al. 2018).

Wildlife

Avian species decline Of the 358 avian species in California, 36% of them are considered to be vulnerable to climate change with 72% of the state- or federally-listed species among them

(Gardali et al. 2012). Climate change could alter avian communities in both parks, with greater impacts projected under higher emissions scenarios (Wu et al. 2018). Among species currently residing in the parks, summer climate suitability under higher emissions scenarios is projected to improve for 28, remain stable for 47, and worsen for 30. However, winter suitability is projected to improve for 12 species, remain stable for 33, and worsen for 14 (Wu et al. 2018). Eighteen species that reside in the parks are projected to lose climate suitability in over half of their current range in North America in summer and/or winter by 2050, however suitable conditions for these species are not projected to disappear within park boundaries (Langham et al. 2015; Wu et al. 2018). Models for avian species in California, 44 of which currently reside in both parks, project that by 2070, avian range shifts may result in 57% of the state being occupied by novel species assemblages (Steel et al. 2012). Under RCP 8.5, the ratio of potential local colonization of avian species to extirpation is 4:1 in winter and 1:4 in summer in US National Parks (Wu et al. 2018). Results from Wu et al. (2018) indicate that national parks in the Pacific West, including Sequoia and Kings Canyon, had significantly lower ($p < 0.001$) rates of local extirpation and colonization by novel species relative to turnover rates for the United States.

Challenges to recruitment of Sierra Nevada yellow-legged frog Projections of climate-induced variability on snowpack and summer precipitation in both parks may cause large fluctuations in the volume of small lakes at higher elevations, which provide habitat for the endangered Sierra Nevada yellow-legged frog (*Rana sierrae* (Vrendenburg)) (Lacan et al. 2008). Increased variability could lead to more frequent drying of the shallow, fishless ponds where yellow-legged frogs are known to breed and undergo larval development, severely reducing frog recruitment and potentially leading to the extirpation of local frog populations (Knapp and Matthews 2000; Lacan et al. 2008).

Adaptation Options

There are key adaptation options that can reduce the future risks of climate change to natural and managed ecosystems (IPCC 2018). As climate change progresses, managers will be challenged to decide how and where to invest resources to address the many conservation needs in both parks. Nydick and Sydoriak (2014) of Sequoia and Kings Canyon found that similar to patterns in conservation decision making reported in Gray (2011), Kujala et al. (2013), and Michalak et al. (2017), resource managers in national parks and forests in the southern Sierra Nevada can be hesitant to apply modeled results when devising place-based management decisions due to uncertainties within models.

Reducing fire risk and drought mortality through fuels reduction treatments Fuels reduction treatments such as prescribed fire and hand thinning of small- and medium-diameter trees are well documented to increase resilience in Sierran mixed-conifer forests (North et al. 2009; Collins et al. 2014). Properly-designed treatments have effectively reduced fire-caused tree mortality under extreme fire weather conditions (Stephens et al. 2009; Fulé et al. 2012; Safford et al. 2012a; Martinson and Omi 2013). Regional reductions of stand density have increased host tree vigor and reduced vulnerability of forest mortality from bark beetles (Fettig et al. 2007). Forest thinning treatments can also increase resistance to drought mortality in Sierran mixed-conifer stands (van Mantgem et al. 2016; Boisrame et al. 2017; Collins et al. 2019). Fuels treatments that aim to improve individual tree resistance to drought and stand resistance to wildfire are critical for maintaining the ecological integrity and ecosystem services of forests (e.g. wildlife habitat, soil stability, and carbon sequestration) (Collins et al. 2014; Stephens et al. 2020). Managers could capitalize on existing treated areas as an “anchor” to facilitate the expanded use of managed wildfire or prescribed fire on the landscape (North et al. 2015).

Conservation of giant sequoia groves Park managers can minimize the risk in the most vulnerable giant sequoia groves while also focusing management efforts on areas of lower vulnerability to increase the likelihood of the long-term persistence of the species (Morelli et al. 2016). Hand thinning of smaller-diameter trees could be applied near the bases of selected giant sequoia before the application of prescribed fire to reduce the risk of severe cambial damage, which may be heightened by future drought stress (Nydick et al. 2018). Giant sequoia could also be planted in areas with projected future suitable habitat, which may be outside current grove distributions (Schwartz et al. 2012). Managers could select seed stock that are more likely adapted to tolerate hotter droughts and other projected future conditions (Erickson et al. 2012). Regardless of what actions are taken, managers should track effectiveness of conservation efforts and ecological responses to identify when changes in management practices may be needed (Stein et al. 2014; Nydick et al. 2018).

Establishing habitat corridors As climate change influences species ranges, park managers can assist elevational and latitudinal migrations by establishing habitat corridors both west to east and north to south (NPS 2013). Forest restoration treatments designed to maintain key habitat features of old growth forests (e.g. retention of large trees and dense canopy of tall trees) may preserve critical habitat for sensitive species like the California spotted owl (*Strix occidentalis occidentalis* (Xantus)) and Pacific fisher (*Pekania pennanti* (Erxleben)) (Tempel et al. 2015; Kramer et al. 2020). Fire management coupled with appropriately-designed restoration treatments in Sequoia and Kings Canyon likely maintains sufficient spotted owl habitat and may contribute to population stability within parks relative to declining populations in surrounding national forests (Kramer et al. 2020).

Carbon Solutions

Vegetation can either remove carbon from the atmosphere or serve as a source of carbon emissions through deforestation, wildfire, and other drivers of mortality (IPCC 2013; IPCC 2014). The balance between emissions and sequestration determines whether vegetation and ecosystems in general are exacerbating global climate change. Forests store large amounts of carbon in their aboveground and belowground biomass, meaning the management of forest ecosystems will critically influence global vegetative carbon storage and climate-related risks over the next century.

Sequoia forests in the Sierra Nevada, including those in Sequoia and Kings Canyon, have the second highest aboveground biomass in the world, storing up to 1400 Mg C/ha (Sillett et al. 2019). Within park boundaries, western Sequoia and southwestern Kings Canyon store aboveground carbon at the highest densities (Figure 10; Gonzalez et al. 2015). From 2001 to 2010, those same areas experienced the greatest losses of stored carbon (Figure 11; Gonzalez et al. 2015). California wildland ecosystems lost more carbon than they gained from 2001 to 2015, with wildfires causing two-thirds of the loss (Gonzalez et al. 2015). In an NPS (2013) analysis of carbon stored in live vegetation in National Parks in the Sierra Nevada, NPS estimated a potential loss of 0.1 Mg C/ha/year. The decrease in carbon stock would be in lower-elevation ecosystems while mid- to upper-elevation ecosystems indicated potential increases in productivity. Carbon stocks in frequent-fire forests throughout the western US decreased from 1986 to 2004 (-39±14 Tg C) (Powell et al. 2014). Additionally, fuels reduction treatments in the Sierra can significantly stabilize live tree carbon stocks (Foster et al. 2020). Though treatments can result in immediate removal of live tree carbon, North and Hurteau (2011) report that treatments in Sierran mixed-conifer forests reduce long-term carbon emissions from wildfires by 57%. In untreated stands 70% of the remaining carbon stock post-fire transitioned to decomposing stocks (snags and surface fuels) compared to 19% in treated stands (North and Hurteau 2011).

Sequoia and Kings Canyon are involved in the National Park Service Climate Friendly Parks program. Their participation includes inventorying all human sources of greenhouse gas emissions from both parks (NPS 2008). In 2006, analyses estimated that both parks produced a combined 2700 tonnes of carbon, 66% of which came from vehicular transportation of both staff and visitors. An additional 29% came from electricity use and 6% from a combination of waste disposal and other management activities. Results also indicated that forest management resulted in the sequestration of 150,000 tonnes of carbon. The *Sequoia and Kings Canyon National Park Action Plan* (NPS 2008) identified viable solutions to reduce the park emissions. Proposed solutions included reducing fossil fuel consumption by reducing park vehicle fleet size, limiting energy consumption in all park facilities, designing public transportation systems to limit visitor car use, and reducing the amount of waste produced by park operations.

The Intergovernmental Panel on Climate Change states with high confidence that carbon emissions reductions would allow us to meet international goals of limiting global temperature increase to 1.5 to 2℃ (IPCC 2018). It is evident from the copious amount of research conducted both within the parks and in the region that emissions reductions can significantly reduce warming within park boundaries (Figure 9, Table 5, Table 6) (Gonzalez et al. 2018) and thus reduce risks of other climate-caused ecosystem degradation.

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Figures and Tables

Figure 1: Map of Sequoia and Kings Canyon National Parks (National Park Service 2014).

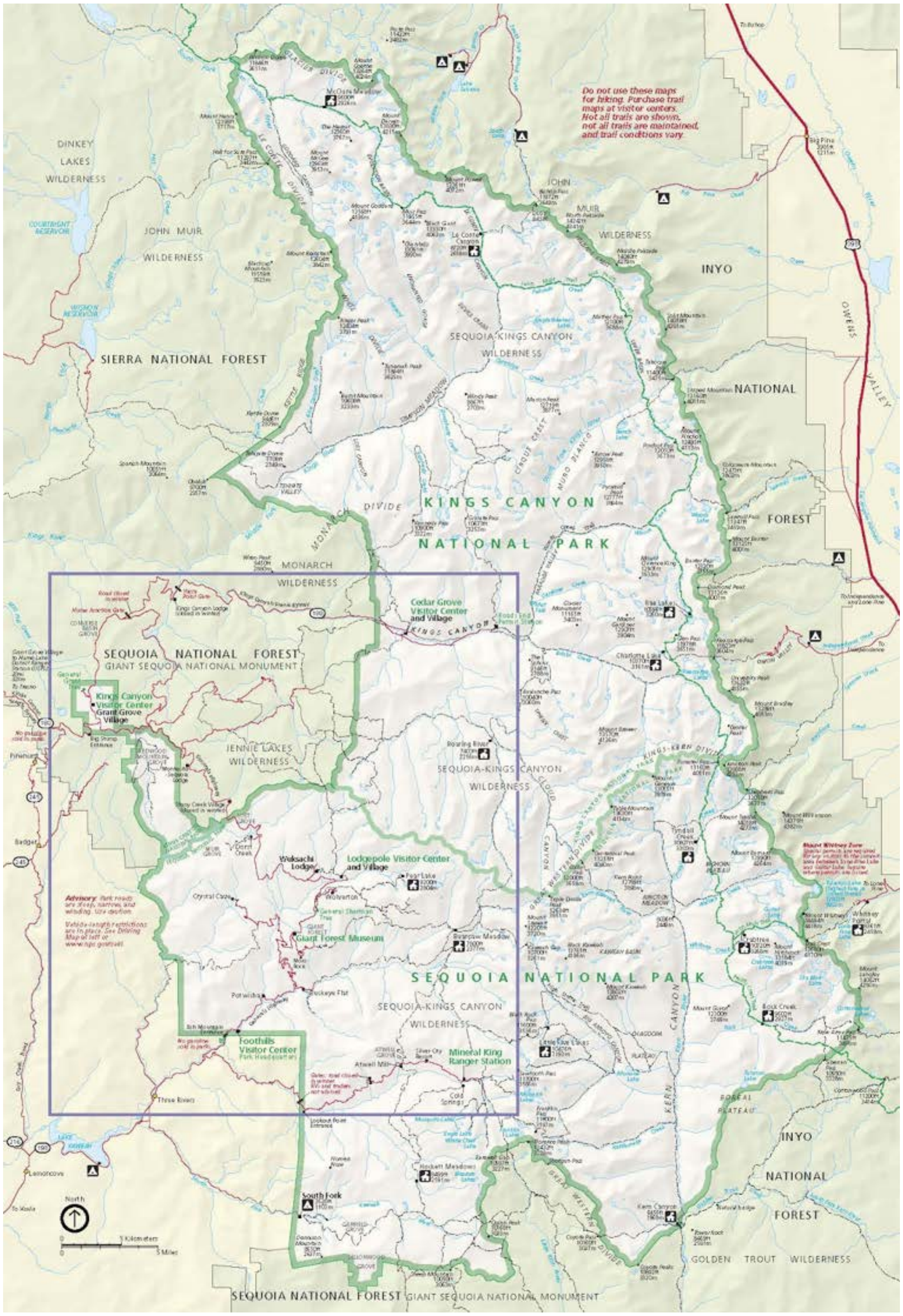
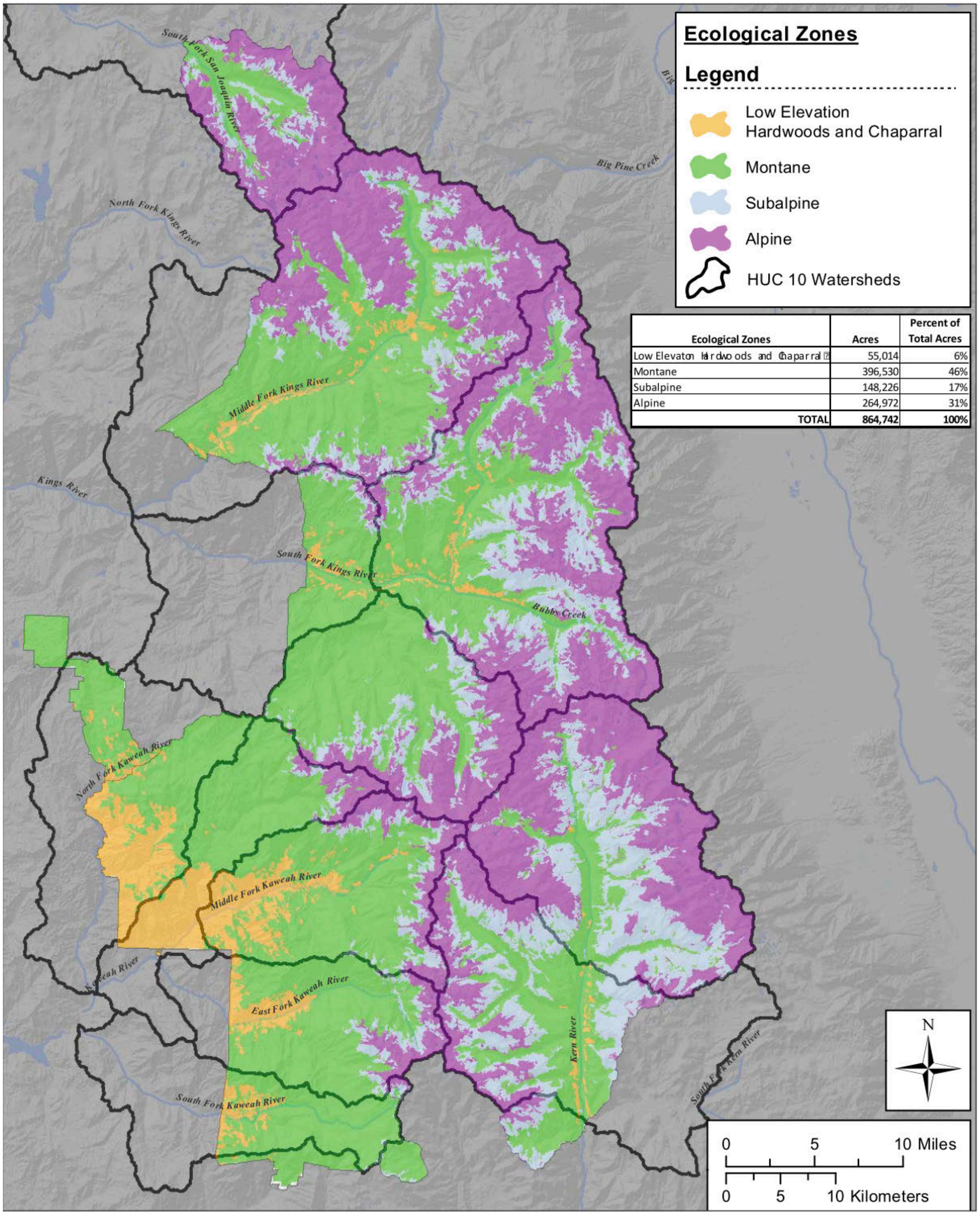


Figure 2: Map of the ecological zones found in Sequoia and Kings Canyon National Parks. The four primary ecological zones (low elevation hardwoods and chaparral, montane, subalpine, and alpine) are shown and overlain with watershed boundaries. Ecological zone area is described in the table in the upper right corner (NPS 2013).



Ecological Zones	Acres	Percent of Total Acres
Low Elevation Hardwoods and Chaparral	55,014	6%
Montane	396,530	46%
Subalpine	148,226	17%
Alpine	264,972	31%
TOTAL	**864,742**	**100%**

Figure 3: Average annual temperature (℃), 1895-2017, for the areas within the boundaries of Sequoia and Kings Canyon, with the trend calculated by linear regression, corrected for temporal autocorrelation (Gonzalez et al. 2018).

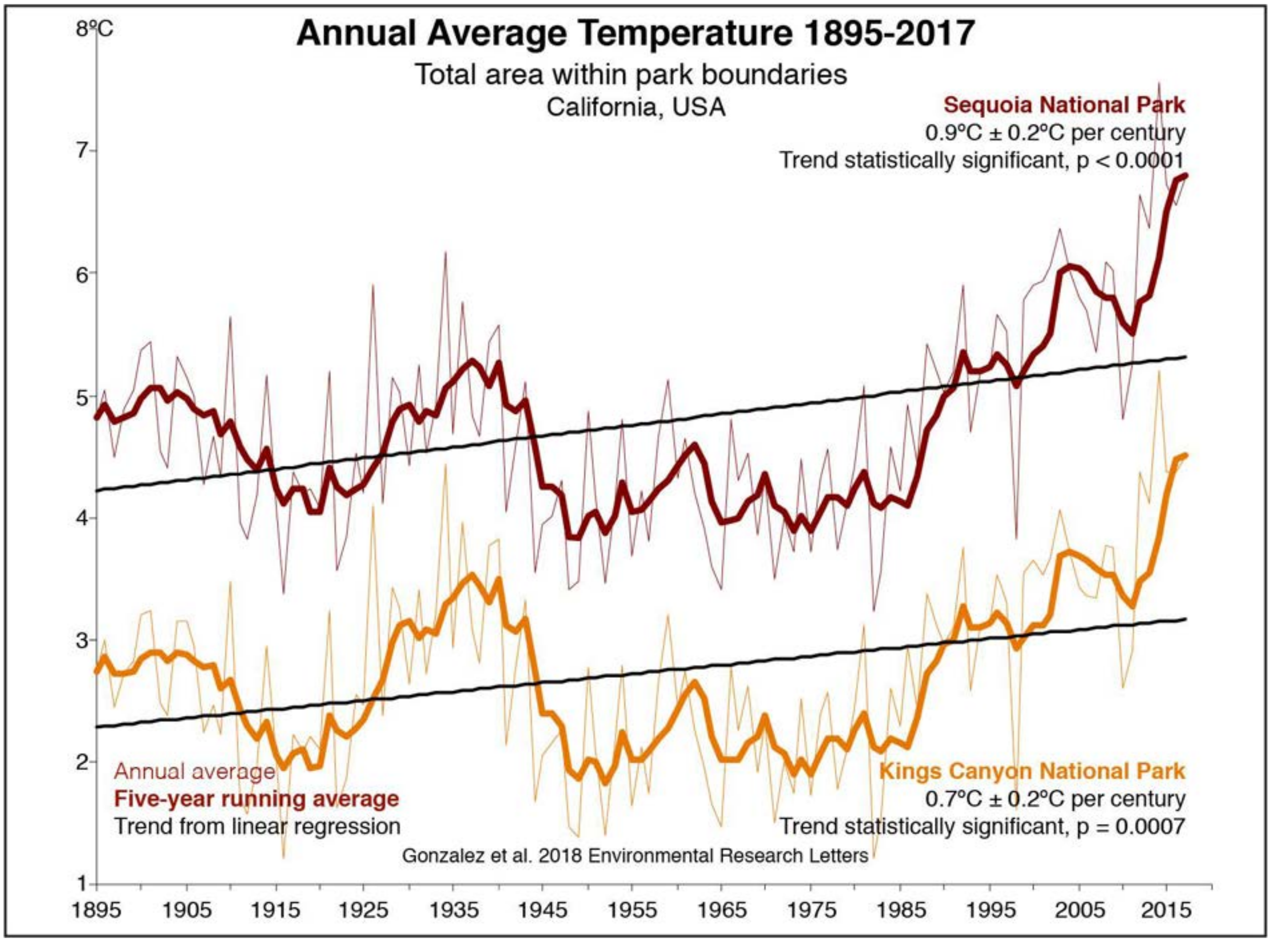


Figure 4: Trend in annual average temperature (℃), 1895-2016, at 800 m spatial resolution, from linear regression, corrected for temporal autocorrelation (Gonzalez et al. 2018).

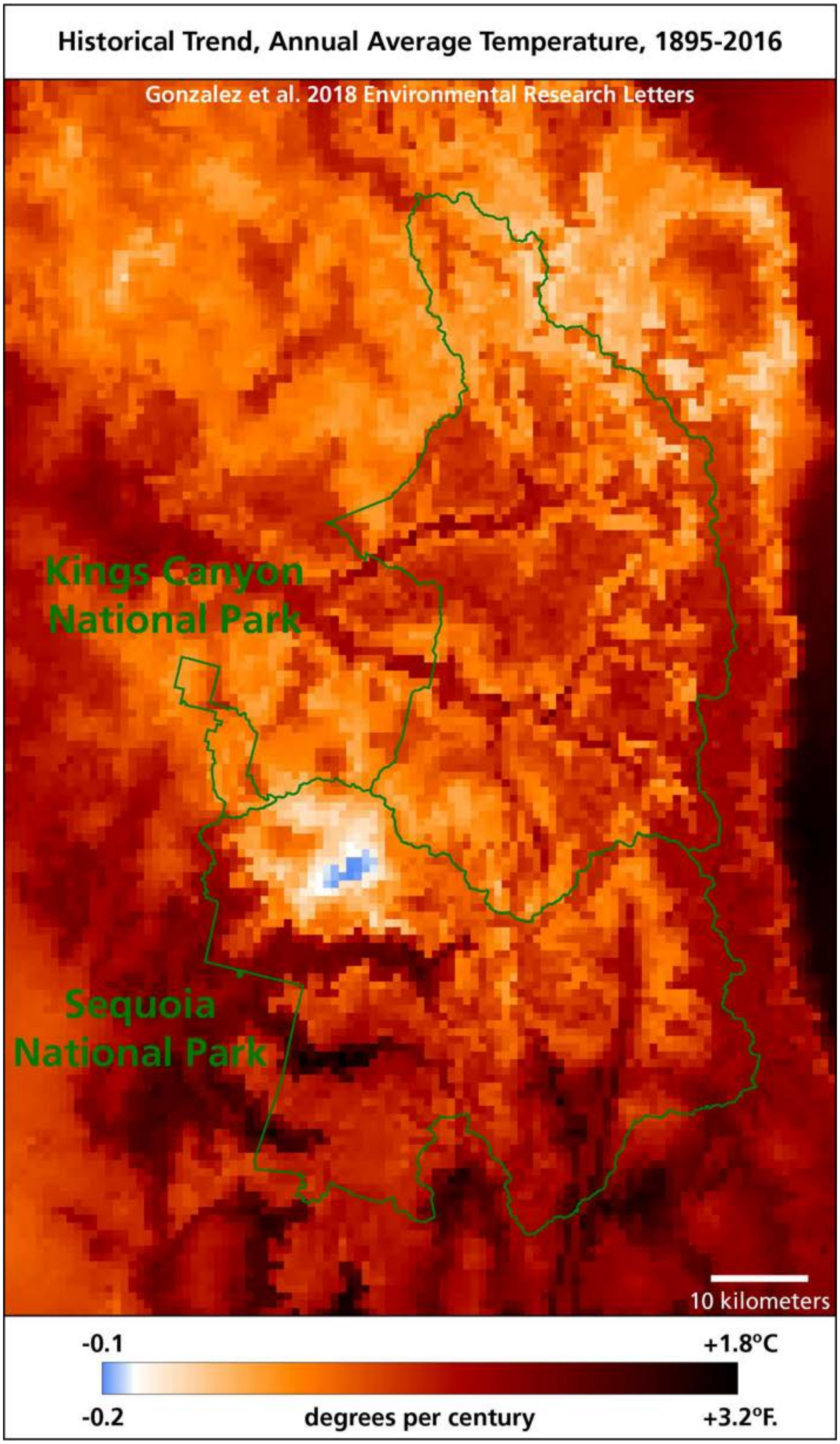


Figure 5: Departures in annual temperature (℃) from the average temperature calculated from a reference period of 1949-1974. The black line represents the five-year running mean of the average of all weather stations. Weather stations are located both within park boundaries (Ash Mountain, Grant Grove, Lodgepole) and in the general region of the parks (Bishop Airport, Independence, Lemon Cove) (Das and Stephenson 2013).

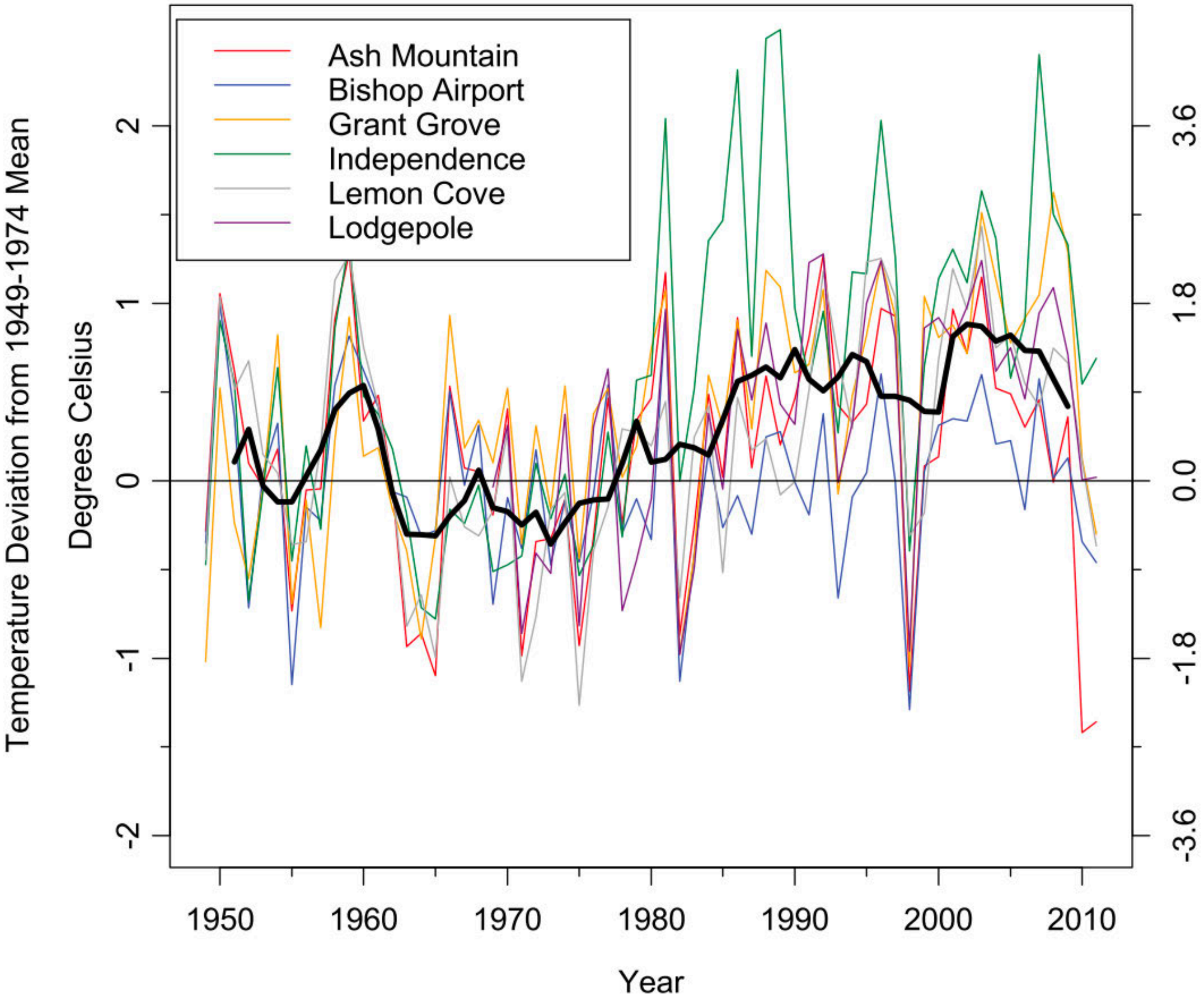


Figure 6: Total annual precipitation (mm/yr), 1895-2017, for the areas within the boundaries of Sequoia and Kings Canyon (Gonzalez et al. 2018).

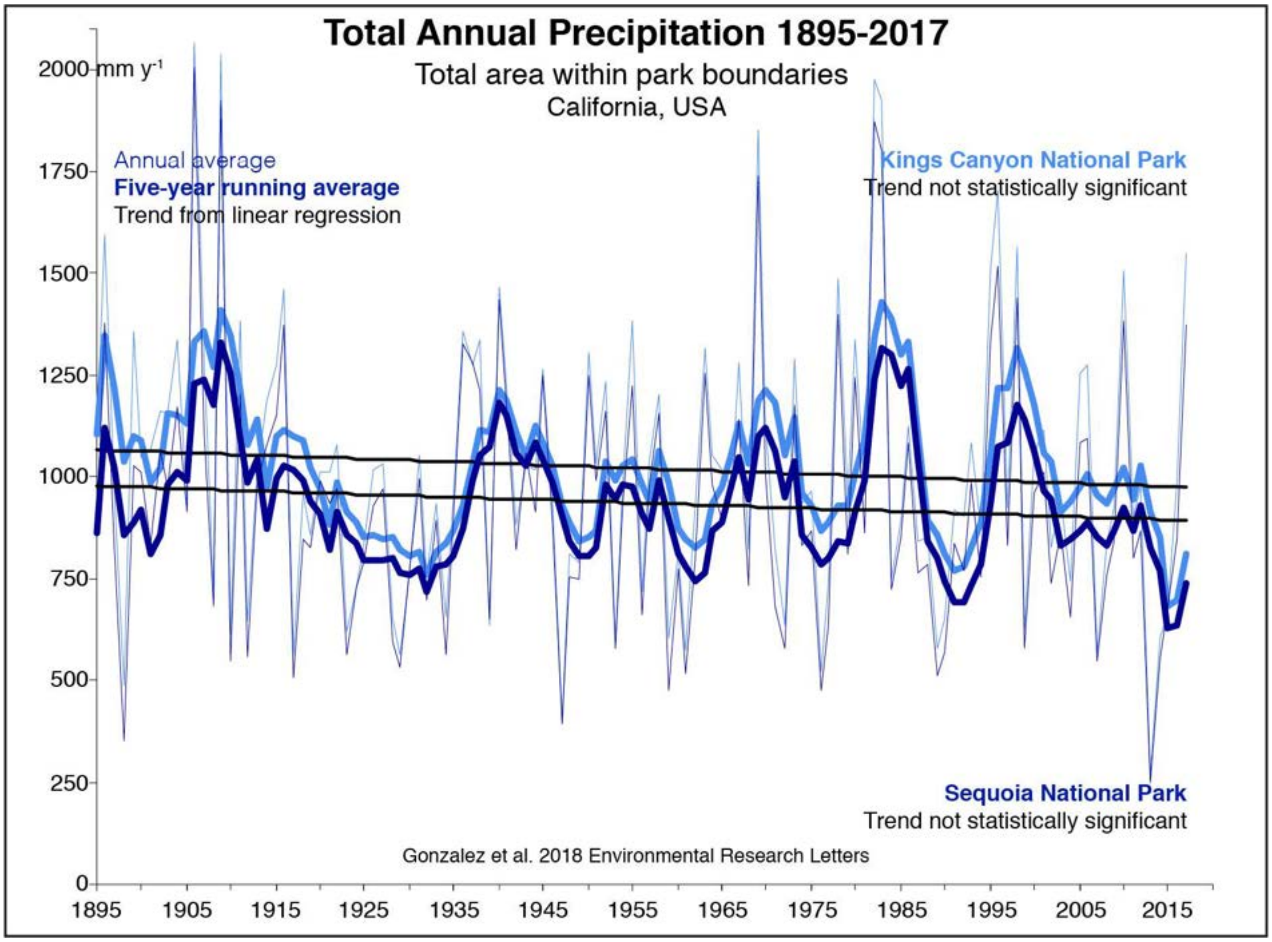


Figure 7: Trend in total annual precipitation (% per century), 1895-2017, at 800 m spatial resolution, from linear regression, corrected for temporal autocorrelation (Gonzalez et al. 2018).

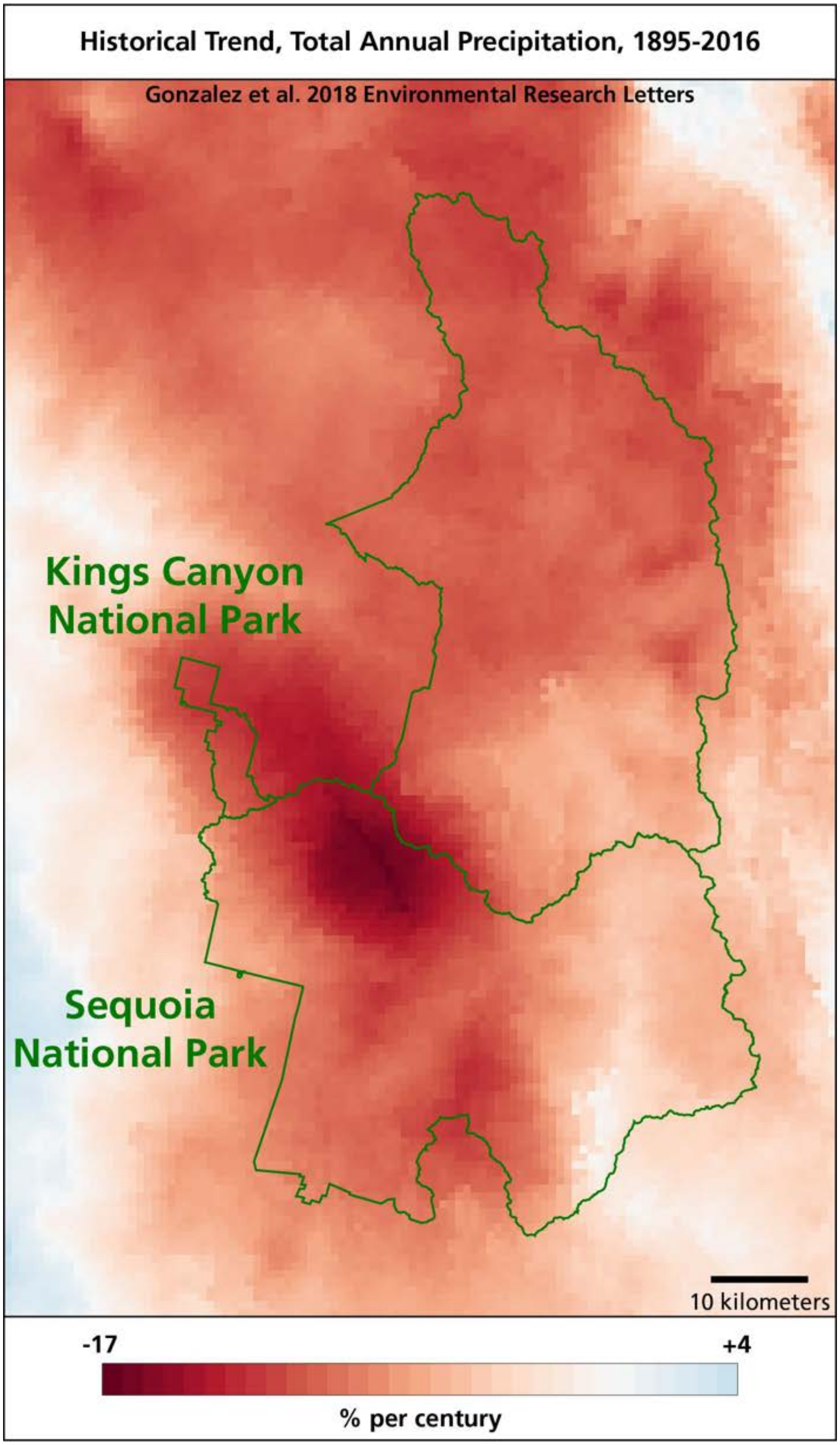


Figure 8: Deviations in annual precipitation (%) from the average temperature calculated from a reference period of 1949-1974. The black line represents the five-year running mean of the average of all weather stations. Weather stations are located both within park boundaries (Ash Mountain, Grant Grove, Lodgepole) and in the general region of the parks (Bishop Airport, Independence, Lemon Cove) (Das and Stephenson 2013).

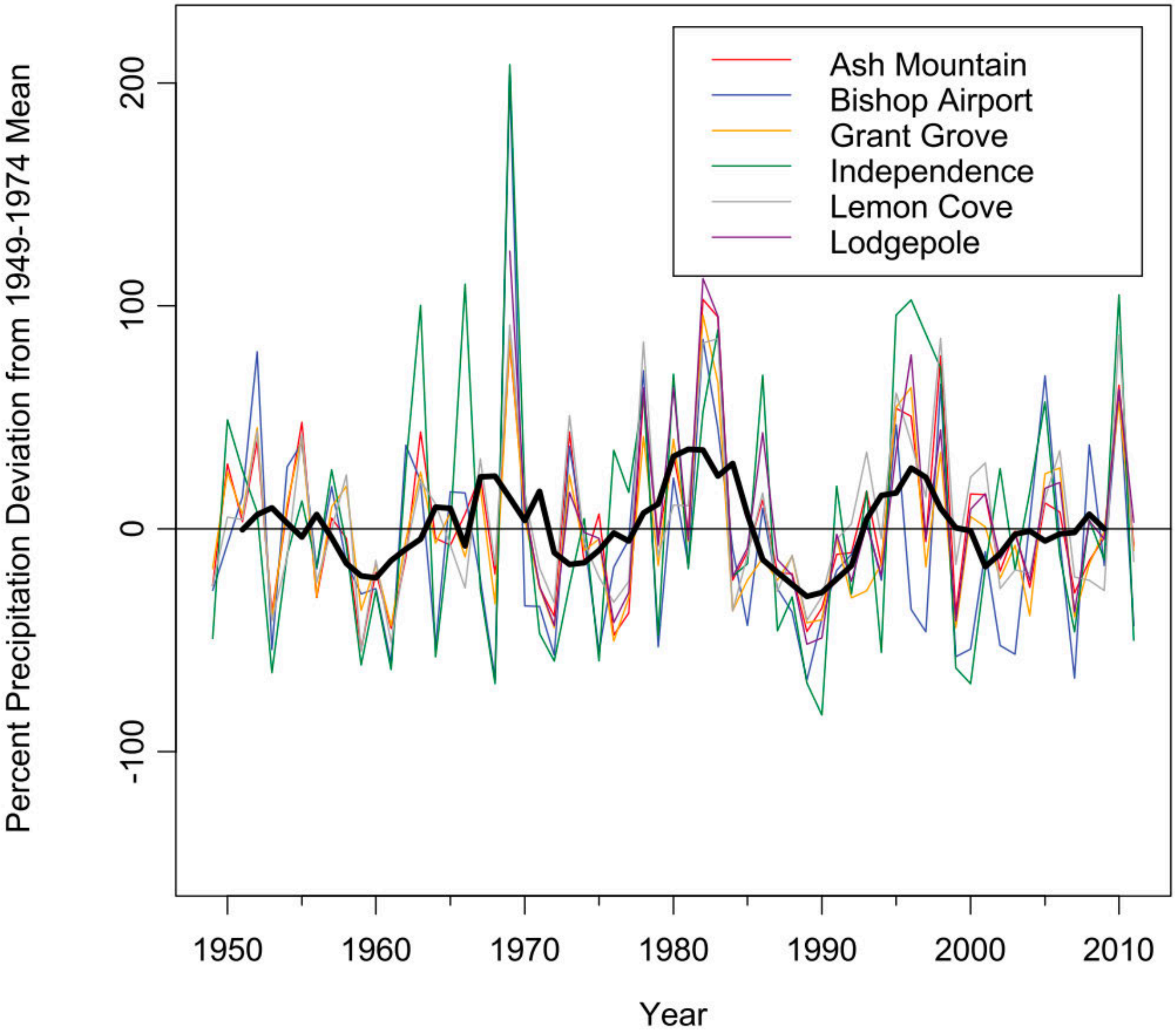


Figure 9: Projections of future climate for the area within the boundaries of Sequoia National Park, relative to 1971-2000 average values (Gonzalez et al. 2018). Each small dot is the output of one of 121 runs of 33 general circulation models. The large color dots are the average values for the four IPCC emissions scenarios. The crosses are the standard deviations of the average values.

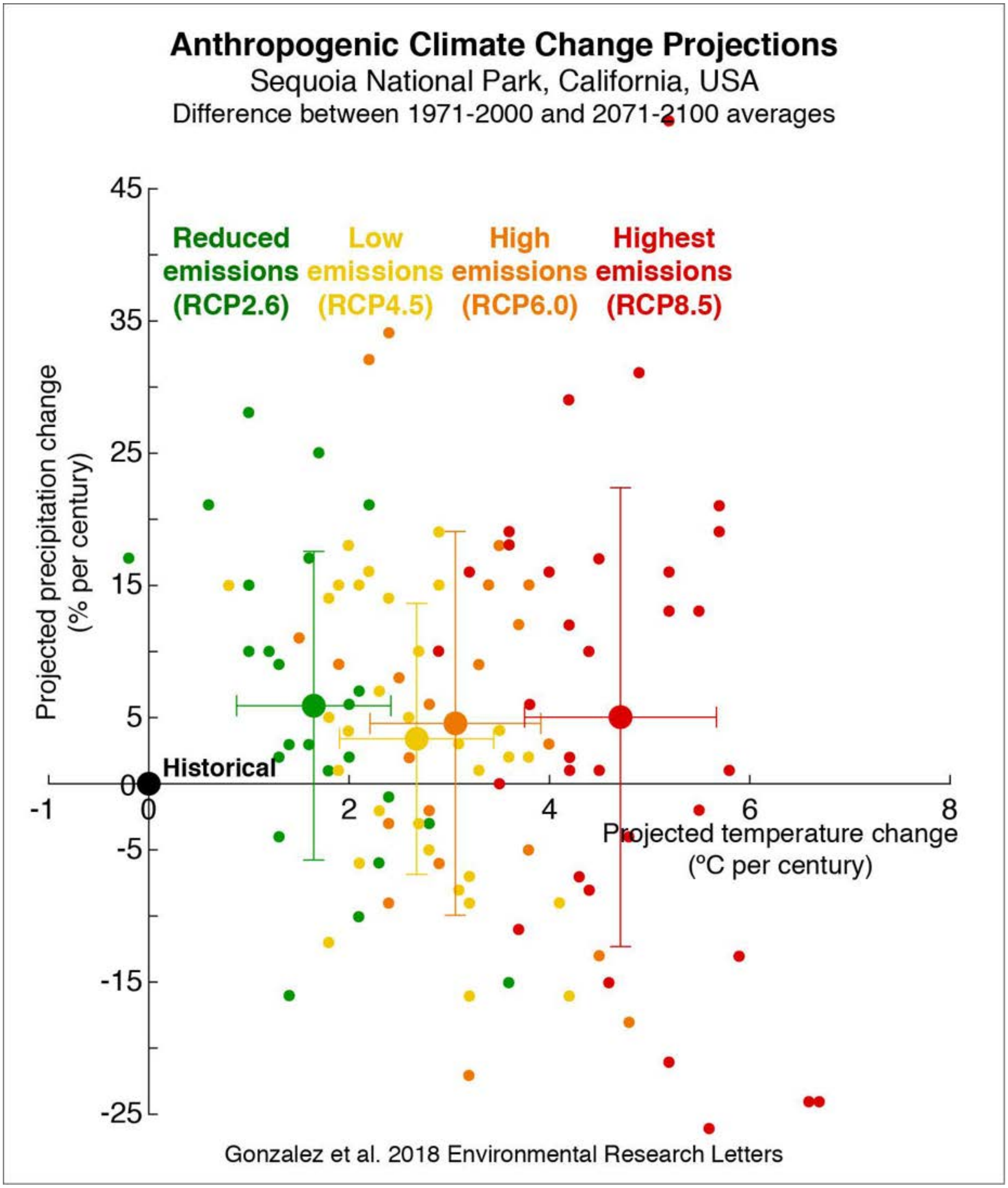


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Figure 10. Aboveground vegetation carbon in 2010, across Sequoia and Kings Canyon National Parks (Gonzalez et al. 2015). Darker shades indicate more Megagrams of carbon stored per hectare.

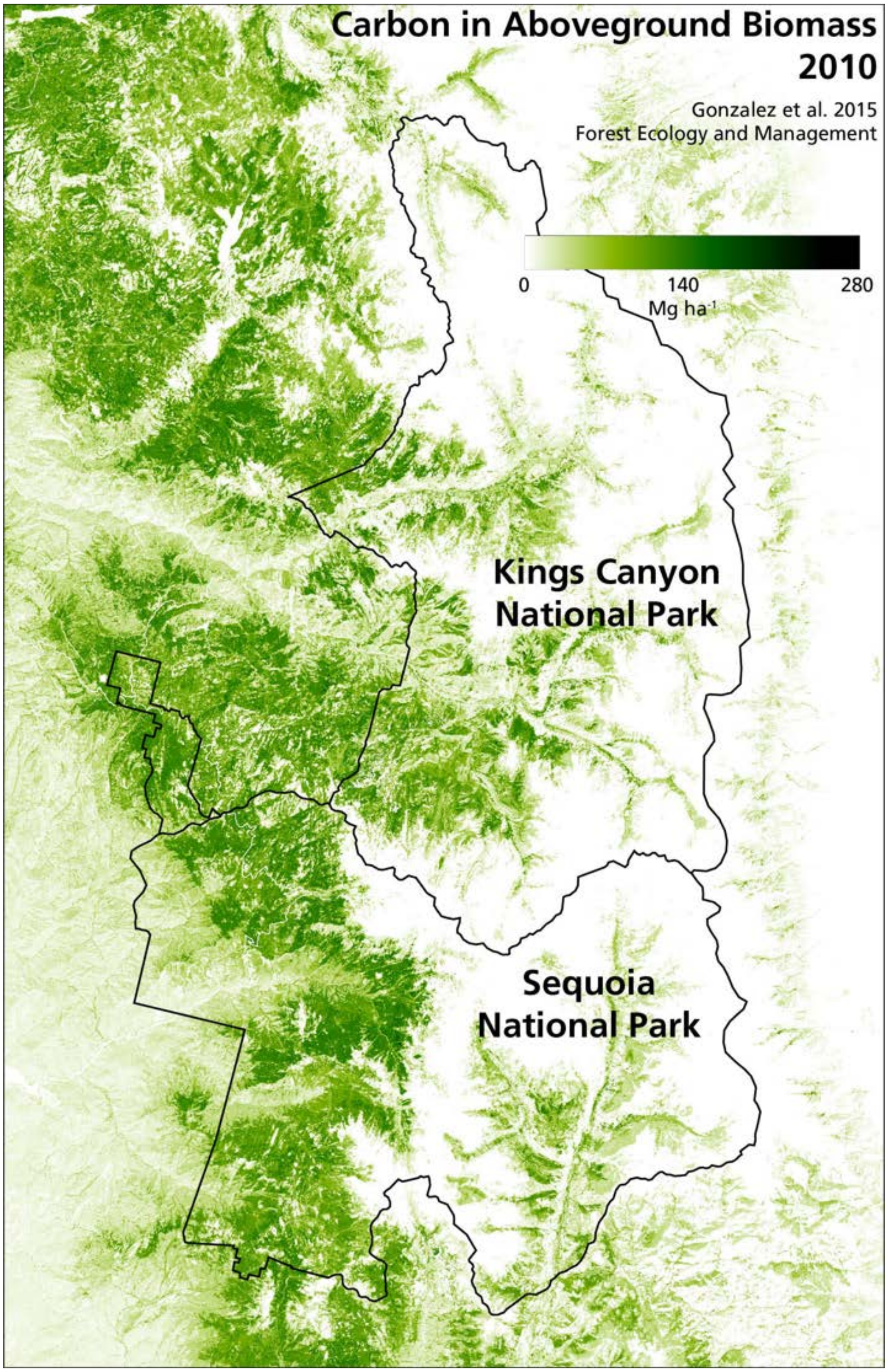

Figure 11: Aboveground vegetation carbon change, 2001-2010, across Sequoia and Kings Canyon National Parks (Gonzalez et al. 2015).

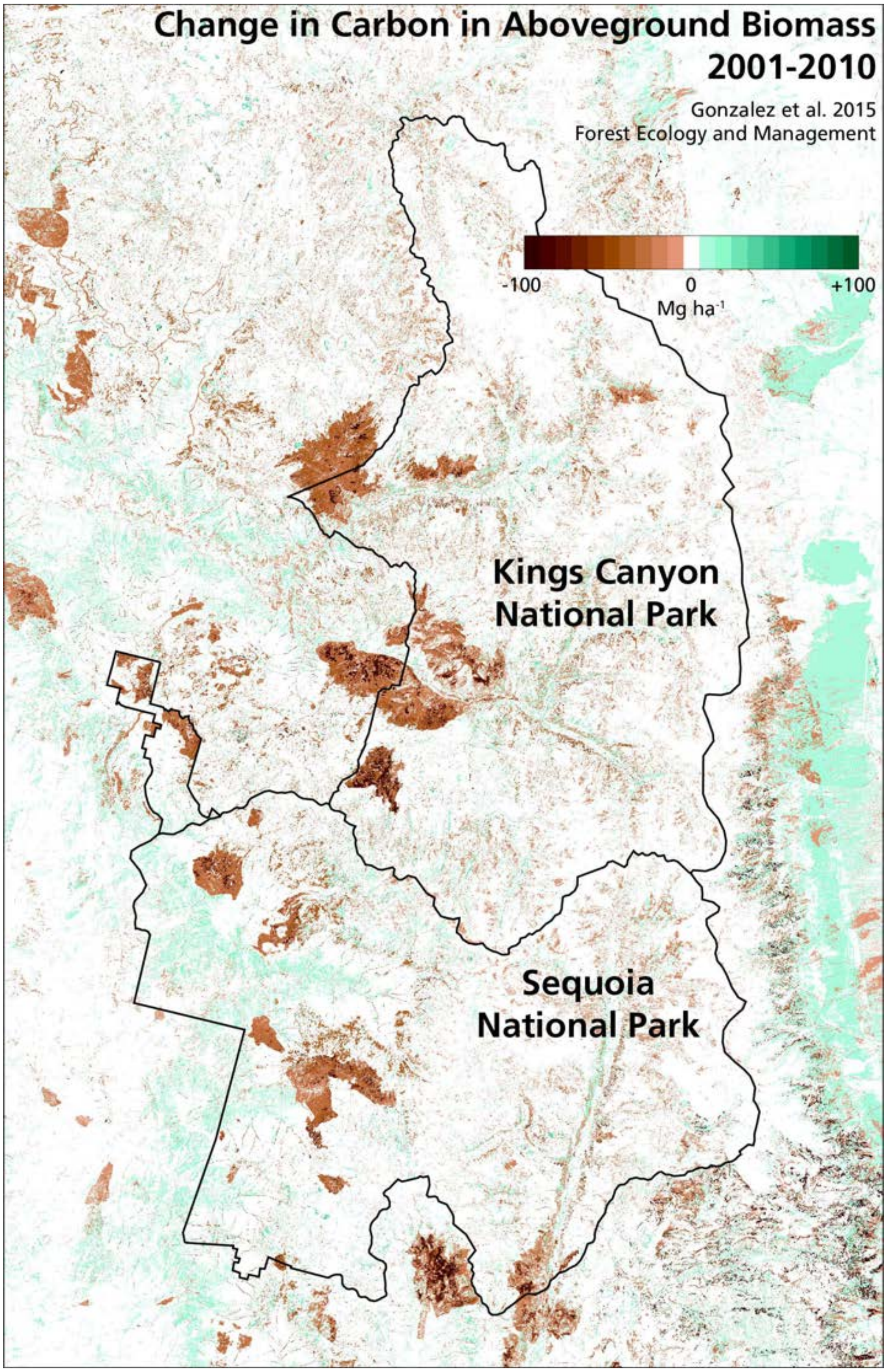

Table 1. **Historical average temperatures** and trends for the area within the boundaries of Sequoia National Park (Gonzalez et al. 2018). SD = standard deviation, SE = standard error, sig. = statistical significance, * *P* ≤ 0.05, ** *P* ≤ 0.01, *** *P* ≤ 0.001.

	1971-2000		1895-2010			1950-2010		
	mean	SD	trend	SE	sig.	trend	SE	sig.
	ºC		ºC century^{-1}			ºC century^{-1}		
Annual	4.7	0.6	0.3	0.2		1.4	0.5	**
December-February	-2	1.2	0	0.3		0.7	0.7	
March-May	2.4	1.5	0.6	0.4		2.4	1	*
June-August	12.6	0.9	0.4	0.3		2	0.8	*
September-November	5.7	1.3	0.3	0.3		0.7	0.8	
January	-2.1	1.5	0.2	0.5		2.5	1	**
February	-2.1	1.6	0.2	0.4		0.3	1	
March	-0.7	1.9	0.4	0.6		3.3	1.3	*
April	1.9	2.1	0.1	0.5		0.9	1.5	
May	5.9	2	1.3	0.4	**	2.9	1.1	*
June	10.4	1.4	0.5	0.5		2.2	1.3	
July	13.7	1.2	0.4	0.4		1.7	1.1	
August	13.5	1.2	0.4	0.3		2	0.8	*
September	10.3	1.5	0.8	0.4		1.3	1.1	
October	5.8	1.8	0.6	0.5		0.2	1.3	
November	1.1	1.9	-0.6	0.5		0.7	1.2	
December	-1.6	2.1	-0.4	0.6		-1	1.6	

Table 2. **Historical average temperatures** and trends for the area within the boundaries of Kings Canyon National Park (Gonzalez et al. 2018). SD = standard deviation, SE = standard error, sig. = statistical significance, * *P* ≤ 0.05, ** *P* ≤ 0.01, *** *P* ≤ 0.001.

	1971-2000		1895-2010			1950-2010		
	mean	SD	trend	SE	sig.	trend	SE	sig.
	ºC		ºC century^{-1}			ºC century^{-1}		
Annual	2.6	0.6	0.4	0.3		1.5	0.5	**
December-February	-3.7	1.2	0.2	0.3		0.7	0.7	
March-May	0.2	1.5	0.6	0.4		2.4	1	*
June-August	10.3	0.9	0.5	0.3		2.3	0.9	*
September-November	3.7	1.3	0.4	0.3		0.8	0.8	
January	-3.8	1.6	0.4	0.5		2.6	1	*
February	-4	1.7	0.3	0.4		0.2	1	
March	-2.6	1.9	0.5	0.6		3.3	1.3	*
April	-0.5	2.2	0	0.5		0.9	1.5	
May	3.8	2.1	1.2	0.5	**	2.9	1.1	*
June	8.1	1.5	0.5	0.5		2.4	1.3	
July	11.5	1.2	0.5	0.4		2.1	1.2	
August	11.3	1.2	0.5	0.4		2.4	0.9	**
September	7.9	1.5	0.9	0.4	*	1.6	1.1	
October	3.7	1.9	0.7	0.5		0.2	1.3	
November	-0.6	1.9	-0.5	0.5		0.7	1.3	
December	-3.2	2.1	-0.3	0.6		-1	1.6	

Table 3. **Historical average precipitation** totals and trends for the area within the boundaries of Sequoia National Park (Gonzalez et al. 2018). 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	908	341	3	9		14	26	
December-February	474	246	4	13		12	32	
March-May	265	155	-10	14		7	36	
June-August	26	21	43	24		88	65	
September-November	150	92	14	21		-17	55	
January	175	133	-9	23		13	55	
February	164	125	2	19		61	47	
March	159	119	-17	21		23	52	
April	73	58	6	18		-25	48	
May	33	29	-23	24		32	69	
June	14	19	23	35		71	103	
July	6	9	98	35	**	186	72	*
August	6	8	34	38		13	109	
September	22	29	-2	40		-49	101	
October	39	32	7	26		129	70	
November	89	74	21	27		-67	76	
December	128	101	29	23		-2	64	

Table 4. **Historical average precipitation** totals and trends for the area within the boundaries of Kings Canyon National Park (Gonzalez et al. 2018). 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	962	342	-5	9		19	25
December-February	508	259	-4	13		18	31
March-May	286	160	-15	13		18	35
June-August	31	20	28	18		43	46
September-November	144	86	3	19		-11	51
January	179	137	-20	23		24	56
February	185	138	-6	19		66	47
March	167	124	-27	21		36	49
April	81	59	9	18		-18	45
May	39	32	-22	22		42	65
June	15	17	12	30		40	90
July	8	9	67	24	**	60	46
August	8	8	14	28		25	86
September	24	27	-23	33		-52	83
October	40	31	-1	26		136	71
November	80	64	12	26		-67	73
December	137	110	21	22		-11	62

Table 5. **Projected temperature increases** (ºC), 2000 to 2100, for the area within the boundaries of Sequoia National Park (Gonzalez et al. 2018), 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	0.7	2.7	0.8	3.1	0.8	4.7	0.9
December-February	1.6	0.7	2.4	0.8	2.7	0.9	4.1	1
March-May	1.5	0.7	2.2	0.9	2.7	0.8	4	1.1
June-August	1.7	1	2.9	1	3.4	1	5.2	1.1
September-November	1.8	0.8	3.2	1.6	3.4	1	5.5	1.8
January	1.7	0.8	2.4	0.8	2.7	0.9	4	1
February	1.5	0.8	2.2	0.8	2.7	0.9	3.9	1
March	1.6	0.9	2.1	0.8	2.6	0.8	3.8	1.1
April	1.4	0.7	2.1	1	2.6	0.8	3.9	1.1
May	1.6	0.8	2.5	1.2	3	1.1	4.4	1.4
June	1.6	1.1	2.7	1.5	3.1	1.2	4.9	1.5
July	1.6	1.1	2.8	1.2	3.4	1.1	5.1	1.3
August	1.7	0.9	3.2	0.9	3.6	0.8	5.6	0.9
September	1.9	0.9	3.4	1.3	3.7	1	5.9	1.5
October	1.8	1	3.3	1.7	3.4	1	5.7	2
November	1.6	0.9	2.9	1.9	3.2	1.1	5	2.2
December	1.6	0.6	2.5	1.3	2.7	0.9	4.3	1.6

Table 6. **Projected temperature increases** (ºC), 2000 to 2100, for the area within the boundaries of Kings Canyon National Park (Gonzalez et al. 2018), 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	1.7	0.8	2.7	0.8	3.1	0.9	4.8	1
December-February	1.6	0.7	2.4	0.8	2.8	0.9	4.1	1
March-May	1.6	0.8	2.3	1	2.8	0.9	4.1	1.1
June-August	1.7	1	3	1.1	3.5	1	5.3	1.1
September-November	1.8	0.9	3.2	1.6	3.5	1	5.6	1.9
January	1.8	0.8	2.4	0.9	2.8	0.9	4.1	1
February	1.6	0.8	2.3	0.8	2.8	0.9	4	1
March	1.6	0.9	2.2	0.9	2.7	0.9	3.8	1.1
April	1.4	0.8	2.1	1	2.7	0.9	3.9	1.1
May	1.6	0.8	2.5	1.2	3	1.1	4.5	1.5
June	1.7	1.1	2.7	1.5	3.2	1.3	5.1	1.5
July	1.7	1.2	2.9	1.3	3.5	1.2	5.2	1.3
August	1.8	0.9	3.2	0.9	3.7	0.9	5.7	0.9
September	1.9	1	3.4	1.3	3.8	1.1	6	1.6
October	1.8	1	3.3	1.7	3.5	1.1	5.8	2
November	1.6	0.9	2.9	1.9	3.2	1.1	5	2.2
December	1.6	0.6	2.5	1.3	2.7	0.9	4.3	1.6

Table 7. **Projected precipitation changes** (%), 2000 to 2100, for the area within the boundaries of Sequoia National Park (Gonzalez et al. 2018), 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	6	12	3	10	5	14	5	17
December-February	6	16	9	18	10	24	16	28
March-May	7	13	-4	12	-1	15	-12	15
June-August	23	44	28	44	13	36	32	60
September-November	2	15	-4	23	-7	15	-7	20
January	7	21	15	26	14	30	25	36
February	9	27	13	26	14	37	22	40
March	7	21	0	15	7	23	0	20
April	8	22	-7	20	-9	22	-21	22
May	7	35	-11	31	-16	23	-32	30
June	13	64	5	69	-11	37	-12	47
July	31	47	36	65	24	60	55	97
August	33	69	57	79	36	58	82	119
September	22	43	23	63	18	51	31	62
October	19	38	-4	31	9	32	2	41
November	-8	17	-10	28	-17	19	-19	27
December	2	20	-3	22	6	22	2	24

Table 8. **Projected precipitation changes** (%), 2000 to 2100, for the area within the boundaries of Kings Canyon National Park (Gonzalez et al. 2018), 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	6	11	4	10	5	14	6	17
December-February	6	16	10	18	11	23	18	27
March-May	8	13	-3	12	0	14	-10	14
June-August	19	37	25	40	11	33	29	56
September-November	3	15	-4	22	-6	16	-6	18
January	8	21	16	26	15	30	26	35
February	9	27	14	25	15	37	23	40
March	7	21	1	15	8	23	2	19
April	10	23	-6	20	-7	21	-19	21
May	7	31	-11	29	-14	22	-30	28
June	10	54	2	58	-11	34	-14	42
July	25	38	32	58	21	53	46	84
August	29	59	53	71	32	52	77	109
September	18	39	21	56	13	42	29	57
October	19	38	-4	30	9	34	1	37
November	-7	17	-10	27	-15	20	-18	26
December	3	20	-2	22	7	22	4	24

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