Climate Change at Muir Woods National Monument, Mill Valley, California, USA

The Redwood Creek trail near Cathedral Grove at Muir Woods National Monument with Redwood Creek (right) visible at high flow after a spring rainstorm (photo C. Jordan)

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Abstract

Anthropogenic climate change is a global occurrence with local consequences. At Muir Woods National Monument (Marin County, California), climate change has resulted in a statistically significant increase in temperature of 1.4℃ ± 0.1℃ per century (mean ± standard error) from 1950 to 2016, with the greatest warming occurring during the spring and summer months (March-August). Precipitation trends were not statistically significant for the historical period. Marin County has also experienced an increase in mean climate water deficit (from 1970 to 2009 as compared with the historical period, 1900-1939), and recent drought events (including the 2012-2014 California drought) in the western United States have been caused in part by anthropogenic climate change. Other regional impacts attributed to anthropogenic climate change include shifts in the winter ranges of avian species, declines in bumble bee populations, and a significant increase in area burned by wildfire. Summer fog frequencies may have changed along the California coast during the 20th century, though land-based observations indicate a decrease and shipboard observations indicate an increase. For the period 2000-2100, temperature is projected to increase at Muir Woods National Monument under all emissions scenarios. Under the reduced emissions scenario, Representative Concentration Pathway (RCP) 2.6, temperature is projected to increase 1.4℃ ± 0.6℃ per century at Muir Woods (mean ± standard deviation). Under the highest emissions scenario, RCP 8.5, temperature is projected to increase 3.8℃ ± 0.8℃ per century. Precipitation is also projected to increase in the coming century, though the uncertainty values are high. RCP 2.6 projects a 5% ± 12% per century (mean ± standard deviation) increase in precipitation at Muir Woods for the period 2000-2100, while RCP 8.5 projects a 9% ± 16% per century increase in precipitation over the same time period. Seasonality of rainfall at Muir Woods is also projected to shift, with mean increases in precipitation in all three-month periods except September-November. Future climatic conditions may lead to shifts in climatically suitable area across the coast redwood range, including at Muir Woods. In addition, future climate impacts increase the threat of high severity wildfire at Muir Woods (a threat potentially exacerbated by the effects of Sudden Oak Death) and the vulnerability of coho salmon and steelhead in Redwood Creek, which are threatened by local extinction. The use of prescribed fire, together with continued restoration of aquatic habitat in and along Redwood Creek, are two adaptation options which may increase ecosystem resilience at Muir Woods. Ultimately, the degree to which adaptation is necessary depends upon our global emissions pathway. Therefore, the optimal solution for climate change challenges at Muir Woods National Monument is reducing carbon emissions at the individual, community, national, and international scales.

Location Description

Muir Woods National Monument is a unit of the National Park Service located in Marin County, California, USA. Muir Woods, designated a National Monument in 1908, is managed by the staff of the larger Golden Gate National Recreation Area. Of the Monument's approximately 554 acres, 240 are classified as old-growth coast redwood (*Sequoia sempervirens*) forest (NPS 2017; Bolsinger and Waddell 1993). Muir Woods is located in a narrow valley at the base of Mt. Tamalpais, home to the lower-elevation reaches of the Redwood Creek watershed, approximately two miles from the Pacific Ocean. Due to its coastal site, Muir Woods receives significant marine influence primarily in the form of ubiquitous fog during the summer months. It is this climate characteristic, together with mild winter temperatures and ample winter precipitation, that have enabled the coast redwoods to thrive throughout a narrow strip of land (approximately 50 km wide and 720 km long) along the California and far southern-Oregon coast (including Muir Woods) for thousands of years (Noss 2000). Climate has historically played a critical role in the distribution of coast redwood and other related species throughout their extensive time on earth (Noss 2000). During the Cenozoic era, redwoods had a much broader geographical distribution, growing throughout mid-northern latitudes in the northern hemisphere (Noss 2000). Shifts in climate around thirty million years ago began to dramatically shrink this distribution, eventually resulting in the limited geographic distribution of coast redwoods today (Noss 2000). Thus, climate is a particularly relevant factor to consider when analyzing the historical and future range and distribution of *Sequoia sempervirens*.

Historical Climate Trends

Temperature and Precipitation Consistent with observed trends averaged across all 419 U.S. National Parks during the historical period (1895-2016), Muir Woods National Monument experienced a statistically significant increase in temperature of 1.4℃ ± 0.1℃ per century (mean ± standard error) for the period 1950-2016, with the greatest warming occurring during the spring and summer months (March-August) (Figures 1, 2, Table 1) (Gonzalez 2016; Gonzalez et al. 2018). The precipitation trend was not statistically significant for the historical period 1895-2016 (Figures 3, 4, Table 2) (Gonzalez et al. 2018). These historical temperature and precipitation trends align with historical data from the other eight national parks which in addition to Muir Woods National Monument constitute the Golden Gate National Recreation Area (Figures 1, 2, 3, 4) (Gonzalez et al. 2016).

Fog Fog frequencies may have changed along the California coast during the historical period. One study inferred a 33% reduction in summer fog frequencies in the coast redwood range for the period 1951-2008 compared with the historical period 1901-1925, based primarily on an analysis of cloud ceiling heights obtained from coastal airports (Johnstone and Dawson 2010).

In contrast to this result are shipboard observations from 1950 to 2007, indicating a 7.4% increase in summer (June, July, August) fog frequencies along the California and Oregon Coasts during the study period. (Dorman et al. 2017). Though the authors discuss the apparent contradiction with Johnstone and Dawson's (2010) findings, they note that this is not necessarily the case, as Johnstone and Dawson (2010) examined cloud ceiling heights on land rather than fog at sea level (Dorman et al. 2017).

Drought Southern Marin County, along with most of the northern Bay Area, has experienced an increase in mean climate water deficit of approximately 25 mm during the modern period (1970-2009) as compared with the historical period (1900-1939) (Rapacciuolo et al. 2014). Water availability is an essential factor for coast redwoods, as large trees (45 m in height) are estimated to require 600 ± 145 liters per day (Dawson et al. 1998).

Broadening the scale, recent drought conditions in the southwestern U.S. have implicated anthropogenic climate change as a causal factor. An analysis of the 2000-2018 megadrought in southwestern North America showed the event to be the most second-most severe since the year 800 and attributed 47% of the drought severity to anthropogenic climate change, exacerbating what would have otherwise been a moderate drought if solely influenced by natural variability (Williams et al. 2020). An earlier analysis examining the California drought of 2012-2014 attributed 8-27% of the drought anomaly to anthropogenic temperature increases (Williams et al. 2015).

An 1100-year analysis of dendrochronological isotopes showed that the redwoods of north-coastal California (a region about 180 miles north of Muir Woods) have not experienced recent and historic megadroughts that have affected the western U.S. (including the 2012-2015 drought as well as events in the 11th and 16th centuries) (Voelker et al. 2018). This result indicates lack of winter precipitation is the dominant factor in these megadroughts (as opposed to greater evaporative demand) and points to the north coast of California as a "relatively stable macro-refugia" (Voelker et al. 2018, page 905).

Historical Impacts

Though no studies to date have examined the impact of historical climatic variations outside the range of natural variability (i.e. anthropogenic climate change) at Muir Woods National Monument, many studies have examined the impacts of climatic shifts regionally.

Sea Level Although Muir Woods National Monument contains no shoreline-adjacent land, sea level in the Golden Gate National Recreation Area has risen 22 ± 1 cm (9 ± 0.4 in.) from 1854 to 2016, an increase that is part of a statistically significant global trend attributed to anthropogenic climate change (Gonzalez 2016; Church and White 2011; IPCC 2013).

Birds Latitudinal shifts in the ranges of winter avian species have been observed in North America and attributed to anthropogenic climate change. An analysis of the winter ranges of 254 avian species in North America from 1975 to 2004 using Christmas Bird Count circle data (including count locations in Marin County) showed the center of abundance experienced a northward shift of about 1 km/year during the study period (La Sorte and Thompson 2007).

Bumble Bees Bumble bee populations have also been affected by anthropogenic climate change. Consistent with a 46% (± 3.3% standard error) average decline in probability of site occupancy in North America, Northern California has experienced a decline in probability of site occupancy for bumble bees in recent years (2000-2014) compared with the historical period (1901-1974) (Soroye et al. 2020).

Wildfire Temperature and vapor pressure deficit increases as a direct result of anthropogenic climate change have been implicated for an additional 4.2 million hectares of burned acreage in western forests in the coterminous U.S. from 1984 to 2015, approximately doubling the area that would have been expected to burn under natural climatic variability (Abatzoglou and Williams 2016).

Fall, the season of Northern California's recent deadly and destructive Sonoma Complex and Camp Fires, has also been affected by changing weather conditions in California attributed to climate change, including a statistically significant increase in temperature and decrease in precipitation from 1979 to 2018 (Goss et al. 2020). Due to these climatic changes, "the mean number of days with extreme fire weather during the autumn season [September through November] has more than doubled" (Goss et al. 2020, page 14).

Climate Projections

Temperature For the period 2000-2100, temperature is projected to increase under all emissions scenarios (Figure 5, Table 3). Under the reduced emissions scenario, Representative Concentration Pathway (RCP) 2.6, temperature is projected to increase 1.4°C ± 0.6°C per century at Muir Woods National Monument (mean ± standard deviation) (Figure 5, Table 3) (Gonzalez et al. 2018). Under the highest emissions scenario, RCP 8.5, temperature is projected to increase 3.8°C ± 0.8°C degrees per century (Figure 5, Table 3) (Gonzalez et al. 2018).

Daily temperature extremes are also projected to increase in the western U.S. under both low and high emissions scenarios. Under the high (RCP 8.5) emissions scenario, changes in the coldest 5-day, 1-in-10-year events are projected to increase over 10°F in the Southwest by midcentury, while changes in the warmest 5-day, 1-in-10 year events are projected to increase over 11°F (Vose et al. 2017).

Precipitation Precipitation is also projected to increase in the coming century, though the uncertainty values are high (Figure 5, Table 4). RCP 2.6 projects a 5% ± 12% per century (mean ± standard deviation) increase in precipitation at Muir Woods for the period 2000-2100, while RCP 8.5 projects a 9% ± 16% per century increase in precipitation over the same time period (Figure 5, Table 4) (Gonzalez et al. 2018).

Seasonality of rainfall at Muir Woods is also projected to shift, with mean increases in precipitation projected in all three-month periods except September-November (Table 4) (Gonzalez et al. 2018). Though future precipitation is especially difficult to model, as reflected by the large standard deviations, a comprehensive analysis of General Circulation Model (GCM) projections showed a mean decrease in precipitation during the September-November period for 2000-2100 across all emissions scenarios (RCP 2.6, 4.5, 6.0, and 8.5), with the greatest increases in mean precipitation projected during the June-August months (Table 4) (Gonzalez et al. 2018).

Anthropogenic climate warming has also increased the probability that dry years in California are also warm ones, a combination that has historically been associated with drought conditions including the recent 2012-2014 event (Diffenbaugh et al. 2015).

Extreme precipitation events are also projected to become more frequent under all emissions scenarios, with a 10% increase in 20-year return period daily precipitation in the western U.S. by mid-century under the low emissions (RCP 4.5) scenario (Easterling et al. 2017). Under the high emissions scenario (RCP 8.5), a 20% increase in 20-year return period daily precipitation is projected across the western U.S. (Easterling et al. 2017).

Risk of decadal (11-year) and multidecadal (35-year) droughts is also projected to increase significantly in the southwest by 2050-2099 under both low (RCP 4.5) and high (RCP 8.5) emissions scenarios, with a ≥80% chance of multidecadal drought occurrence under RCP 8.5 and a >70% chance under RCP 4.5 (compared with a <12% chance during the historical period, 1950-2000) (Cook et al. 2015).

Future Risks

Wildfire Climate change is projected to increase fire risks in California. In Marin County, a recent study projected a 20% increase in fire frequencies in coming decades (2040-2099), with a projected doubling of fire risks “in especially fire prone regions” (Micheli et al. 2016, page 10).

Climate change also threatens to exacerbate fall (September through November) fire conditions in California, through a continuation of observed seasonal warming and drying trends (Goss et al. 2020). Since autumn historically corresponds with offshore Diablo and Santa Ana wind occurrences, these trends indicate “increasing risk that autumn offshore wind events will coincide with critically dry fuels” (Goss et al. 2020, page 17).

The redwood forests of Mt. Tam may be at greater risk of experiencing higher intensity wildfire due to the effects of Sudden Oak Death (SOD), which is widespread in Marin County (Edson et al. 2016). Greater aerial and surface fuels as a result of SOD has been shown to increase fire intensity in coast redwood ecosystems (Metz et al. 2013). However, this intensity increase was dependent on stage of SOD invasion, with late stages resulting in much lower fire intensities due to the decay of tanoak material, as compared with middle stages, in which standing dead tanoaks allowed fire to spread to the canopy of redwoods (Metz et al. 2013). Although Muir Woods and the redwood forests of Marin County were introduced to *Phytopthera* early, in the mid 1990s, affected tanoaks are at various stages of decay, thus complicating the equation.

Locally, the impacts of SOD on fuel loads in coast redwood forests has been examined at nearby Point Reyes National Seashore (Forrestel et al. 2015). Throughout the four-year study period, fuel loads increased across all size classes (1, 10, 100, and 1000 hour), an observation attributed to dead tanoak basal area (Forrestel et al. 2015). The results carried significant implications for fire behavior: "rate of spread and fire line intensity were both an order of magnitude larger for diseased versus healthy stands and predicted flame lengths were three times higher in diseased versus healthy stands" (Forrestel et al. 2015, page 27).

An interesting global relationship should also be noted. Decline in the extent of winter Arctic Sea Ice Extent (ASIE) has been shown to have a statistically significant relationship with wildfire area burned in Northern California for the period 1980-2015, suggesting "reduced wintertime ASIE years are coincident with and may promote summertime atmospheric conditions (i.e., ridging and subsidence) that enhance the likelihood of wildfire in the western U.S." (Knapp and Soulé 2017, page 8).

Vegetation Shifts The present-day range of coast redwoods may be affected by future climatic conditions. An analysis of coast redwood distributions under a warmer climate for the decade 2020-2030 showed a 50% contraction of "climatically suitable area" for coast redwoods in the southern part of the species' range, which includes Muir Woods National Monument, "with no suitable bioclimate remaining south of San Francisco Bay" (Fernandez et al. 2015, page 4146). Under the same climatic forcing, northern coast redwood forests showed a 34% increase in total area, with central redwood forests showing a "stable" response (Fernandez et al. 2015, page 4146). A warmer and wetter future was shown to increase coast redwood area 37% across its range, with the location of Muir Woods shown as stable (Fernandez et al. 2015). All increasingly arid scenarios show a contraction of suitable redwood habitat in the Muir Woods area (Fernandez et al. 2015).

A recent study modeled vegetation vulnerabilities to fifty-four future climate scenarios across a wide range of temperature and precipitation projections (with Mean Annual Temperature increasing 0.69°C by 2070-2099 in the lowest emissions, RCP 2.6, scenario and 5.67°C in the highest emissions scenario, RCP 8.5) in the San Francisco Bay Area (Ackerly et al. 2015). Coast redwood forests showed a trend of decreased extent with increasing Mean Annual Temperature (MAT), and coastal sites, including the area of Muir Woods National Monument, were found to have high vegetation sensitivity to climate change (Ackerly et al. 2015).

Models across climate scenarios consistently show increasing climate water deficits in Marin County, favoring drought-tolerant species (Micheli et al. 2016).

Redwood Growth Sensitivities Dendrochronological analyses in the coast redwood range have shown a negative correlation between dry summer weather and radial tree-ring growth, demonstrating “meaningful climatic variation” (Carroll et al. 2014, page 16). Central and southern redwood forests, which include Muir Woods, showed a negative correlation between maximum spring temperatures and radial growth (Carroll et al. 2014).

By turning to the past, we may be able to attain a better sense of what the future will look like. A paleoclimatological pollen analysis obtained from ocean drilling cores off the Northern California coast (from a location due west of present-day Crescent City) covering the past 16,000 years showed an increase in coast redwood presence in north coast forests beginning around five thousand years ago (Barron et al. 2003). The increase corresponded with a climatic shift from continental (warm and dry with cold winters) to maritime (cool summers with mild winters) and perhaps the establishment of the present-day coastal fog regime (Barron et al. 2003).

Anadromous Fish Recent climatological conditions have negatively affected anadromous fish populations in Northern California. The 2012-2015 drought brought “progressively less suitable habitat conditions for salmonids with each subsequent dry year” in the Russian River Watershed (located approximately 50 miles north of Muir Woods National Monument), likely resulting in severe impacts on steelhead trout and coho salmon, two species which are also found at Redwood Creek in Muir Woods (Deitch et al. 2018, page 1227).

A study on the effects of the recent drought on coho salmon and steelhead trout in Central California in 2015 (Scott Creek, Santa Cruz County, approximately 60 miles south of Muir Woods) showed consistently higher abundance and growth rates for steelhead, potentially suggesting greater vulnerability for coho salmon (Osterback et al. 2018).

Future climate conditions threaten the viability of salmon populations in California. A study of twenty-eight Northeastern Pacific fish species ranges, including coho salmon (*Oncorhynchus kisutch*) and steelhead (*Oncorhynchus mykiss*) projected a poleward average range shift of 18.9 ± 0.5 km per decade under RCP 2.6 and 30.1 ± 0.63 km per decade under RCP 8.5 for the period 2000 to 2060 due to climate change (Cheung et al. 2015). The highest local extinction rates under the SRES A2 emissions scenario (by 2050, relative to 2005) are projected to be in the California Current region, including the waters off the central California coast (Cheung et al. 2015). Another study found 78% of California’s thirty-two native salmonid species face local extinction or extirpation in future decades, with climate change and other human impacts driving the decline (Katz et al. 2013).

A recent climate vulnerability assessment based on present conditions of West Coast anadromous salmonids, examining twenty biological attributes accounting for sensitivity, climate exposure, and adaptive capacity, showed Central California Coast Coho with a “High” exposure and “Very High” sensitivity rating, coupled with “Low” adaptive capacity, a potentially dangerous combination (Crozier et al. 2019). Central California Coast Steelhead, also present at Muir Woods, were rated at “High” exposure, “Moderate” sensitivity, and “Moderate” adaptive capacity levels, perhaps indicative of less vulnerability (Crozier et al. 2019).

One key element of coho salmon habitat is the late-summer contribution of cool water to streams, which is influenced by both Fog and Low Cloud Cover (FLCC) and watershed recharge (Torregrosa et al. 2020). A recent study examined these variables using two future climate projections, “cool” and “hot” for the period 2040-2069. Under the “cool” model, just 6% of the Redwood Creek watershed area was projected to be above 21.5°C, designated as a thermally inhospitable threshold for coho. In contrast, under the “hot” scenario, 36% of Redwood Creek’s watershed area is projected to exceed the threshold (Torregrosa et al. 2020).

Increased stream water temperatures may also increase black spot infection rates in steelhead trout, as was shown in a study on the South Fork of the Eel River (Mendocino County), indicative of an additional potential future stressor to an already vulnerable species (Schaff et al. 2017).

Fog and Water Availability Given that fog is an essential source of water for coast redwoods, constituting perhaps 34% of its annual hydrologic input via fog drip (a smaller contribution comes via foliar uptake), future fog frequencies are critical for understanding the fate of the species (Dawson 1998; Burgess and Dawson 2004). Fog also helps coast redwoods retain water by lowering the atmospheric vapor pressure deficit responsible for evaporation and transpiration from the trees (Burgess and Dawson 2004).

Fog, however, is difficult to model due to the number of variables on which its occurrence relies. However, recent studies have attempted to model future fog frequencies under future climate scenarios. One study projected an increase in fog frequencies in the eastern North Pacific during boreal summer, driven primarily by a weakening of the North Pacific high-pressure system, though these projected increases are in the single-digits (Kawai et al. 2018). The possible effect of increasing inland temperatures enhancing the coast-inland temperature gradient and leading to increased fog frequencies has also been discussed (Torregrosa et al. 2020; Francis et al. 2020). The results of such a pattern, however, may not be straightforward: “This could lead to either less fog due to additional entrainment of moisture into the dry subsiding layer, or more fog from the stronger advection of moist air inland” (Torregrosa et al. 2020, page 154). Amidst the future fog frequency conjecture there have been speculative theories including the following; “Might the increasing aerosol load from higher frequency fires in California fires have the unexpected result of more summertime FLCC?” (Torregrosa et al. 2020, page 154).

A recent fine scale (10 m resolution) analysis of coast redwood habitats found fog frequency to be the most important factor in redwood densities on Mt. Tamalpais (including Muir Woods), exceeding soil water storage and heat load index, among other variables (Francis et al. 2020). Increasing fog frequency, however, did not correspond with increasingly higher redwood densities on Mt. Tam; fog frequencies above 30% were linked to low redwood densities, a result the authors speculatively attribute to coastal sites with high winds and sea salt deposition, and/or microclimatic variations in direct exposure to fog and thus enhanced or reduced fog drip (Francis et al. 2020). Across all study sites, redwood densities corresponded with Interpolated Height Above a Stream (IHAS), with densities decreasing with increasing IHAS value (Francis et al. 2020). The results point to the limitations of coarse-scale, single-factor redwood habitat suitability analyses, and the importance of multi-factor analyses for determining potential microrefugia for coast redwoods, especially sites close to streams, as the climate changes (Francis et al. 2020).

Adaptation Options

Wildfire Coast redwoods, though not fire-dependent, are certainly a fire-adapted and fire-resistant species. Their thick and fibrous bark, high concentration of tannins in bark and wood, and ability to re-sprout from burl tissue all contribute to the fire resilience of the species. Though the degree to which fire is a critical disturbance in coast redwood ecosystems has been debated in the literature and likely varies by site, fire does serve numerous ecological roles including: reducing surface fuel loads, optimizing ground for seed germination, promoting reproduction via sprouting, clearing competing understory vegetation, and improving wildlife habitat (Brown and Baxter 2003; Stephens and Fry 2005; GGNRA 2005).

Historically, the only non-anthropogenic source for fires in the redwood belt was lightning; however, lightning storms typically corresponded with the winter rainy season in California and thus did not lead to frequent ignitions (Stephens and Fry 2005). Therefore, it is believed that Native Americans were responsible for many of the ignitions in the redwood forest in the recent past (Brown et al. 1999).

The alluvial flats of Muir Woods, however, have not experienced significant wildfire in over 150 years. The return of prescribed fire to the Muir Woods ecosystem has been proposed by Park Managers for decades and was even briefly enacted in the late 1990s. The most recent fire management plan of 2015 stated: "The exclusion of fire from the Monument over most of past century and a half has perpetuated and increased the likelihood of higher-intensity fires to occur. Prescribed fire will be used in the redwood/Douglas-fir forest to restore the role of fire to this ecosystem" (GGNRA 2015, page 26).

A primary concern of Park Service staff continues to be the potential for high intensity wildfire as a result of increased surface fuel loads leading to high severity canopy fire, a threat exacerbated by climate change. Such a situation would lead to mortality of old-growth trees in the park, damaging the "pristine character of the National Monument," the protection of which is the National Park Service's top management priority (GGNRA 2005; GGNRA 2015, page 26). In addition, there are concerns regarding the buildup of fuels in areas of the Monument in close proximity to people's homes and the infrastructure of Panoramic Highway and Homestead Valley (GGNRA 2005; GGNRA 2015). The three objectives for fire management in Muir Woods have remained unchanged from the 2005 report to the 2015 report: "restore the role of fire in the relevant vegetation communities; reduce fuel loading and the threat of catastrophic wildfire; and further study fire effects in old-growth coast redwood forest" (GGNRA 2015, page 26).

The return of prescribed fire to Muir Woods would serve two primary purposes: 1) reduce fuel loads thereby reducing the likelihood of high intensity fire, mitigating risk to human lives and infrastructure and old-growth redwood trees, and 2) restore the local role of fire and further study effects of fire in coast redwood ecosystems.

Redwood Creek Restoration Recent efforts to restore the Redwood Creek watershed, including the segment of the watercourse which flows through Muir Woods National Monument, may increase the resilience of the ecosystem to the effects of climate change. Recent priorities of restoration efforts include removal of human-installed stone rip-rap along the Creek banks, which increase stream velocity thus increasing erosion and degrading salmon habitat (NPS 2019). The removal of the rip-rap should facilitate a more natural stream course, with more bends, pools, and areas of shelter for young fish; in addition, slowing the stream should help retain groundwater both in the stream channel and proximal forest, enhancing resilience during drought periods (NPS 2019).

Carbon Solutions

Mitigation Coast redwood forests in Northern California contain the highest above-ground carbon densities of any ecosystem on earth, reaching nearly 2600 Mg ± 110 Mg per hectare at Jedediah Smith State Park (Van Pelt et al. 2016). At Samuel P. Taylor State Park, about 12 miles northwest of Muir Woods National Monument, total aboveground carbon reaches 970 Mg ± 46 Mg per hectare, a carbon density approximately three times that found in old-growth Amazonian rainforest (Van Pelt et al. 2016; Baker et al. 2004). As such, coast redwood forests have been identified as essential carbon sinks, whose survival and persistence may help mitigate the extent of anthropogenic climate change.

Muir Woods National Monument contains an estimated vegetation carbon stock of 20,000 ± 28,000 t (Gonzalez et al. 2015). Since the average per capita fossil fuel carbon emissions in the U.S. is 4.1 tons per person, the aboveground carbon stock at Muir Woods is equivalent to the annual emissions of approximately 6600 Americans (IEA Atlas of Energy 2020).

The vast majority (94%) of carbon emissions at Golden Gate National Recreation Area (GGNRA) are a result of park visitors, with transportation accounting for nearly all visitor carbon dioxide emissions (NPS 2016). Although just 6% of carbon emissions at Golden Gate National Recreation Area are a result of park operations, GGNRA operations became carbon neutral in 2018, achieved through a combination of renewable electricity usage and carbon offsets (NPS 2020). At Muir Woods, reducing visitor transportation emissions via broader use of shuttle buses is one way to reduce this significant carbon footprint.

The adaptation required to climate change, both at Muir Woods and around the world, ultimately depends on the degree of warming, and subsequent associated impacts. For example, limiting global warming to 1.5℃ rather than 2℃ results in less severe local, and global, impacts. Therefore, the optimal solution for climate change challenges at Muir Woods National Monument is reducing carbon emissions at the individual, community, national, and international scales, thus mitigating the literal degree of change. Four high-impact individual actions that can substantially decrease greenhouse gas emissions include having one fewer child, living car free, avoiding air travel, and eating a plant-based diet (Wynes and Nicholas 2017).

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Figures and Tables

Figure 1. Average annual temperature, 1895-2016, for the area within Muir Woods National Monument boundaries, with the trend calculated by linear regression, corrected for temporal autocorrelation (Gonzalez et al. 2018).

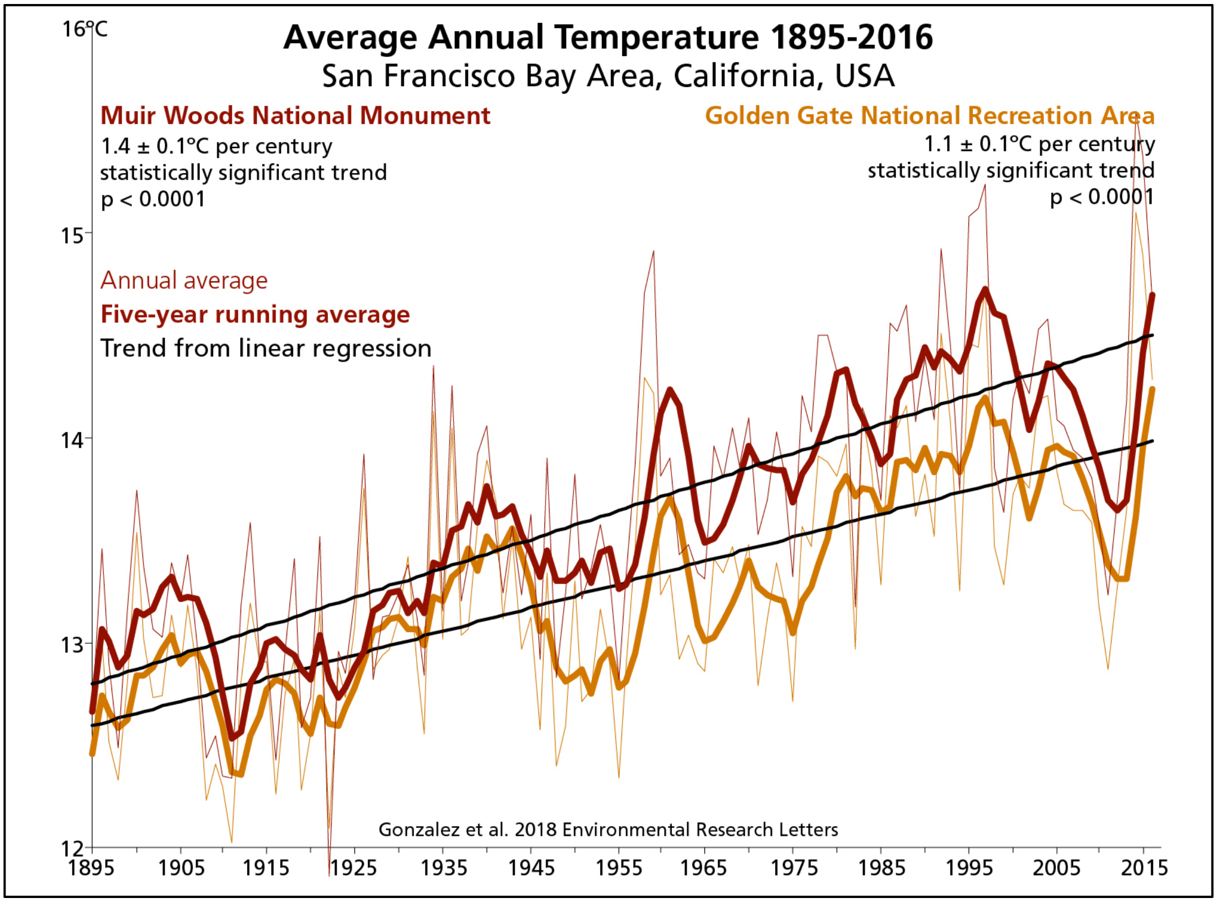

Figure 2. Trend in annual average temperature, 1895-2016, at 800 m spatial resolution, across Muir Woods National Monument, from linear regression, corrected for temporal autocorrelation (Gonzalez et al. 2018).

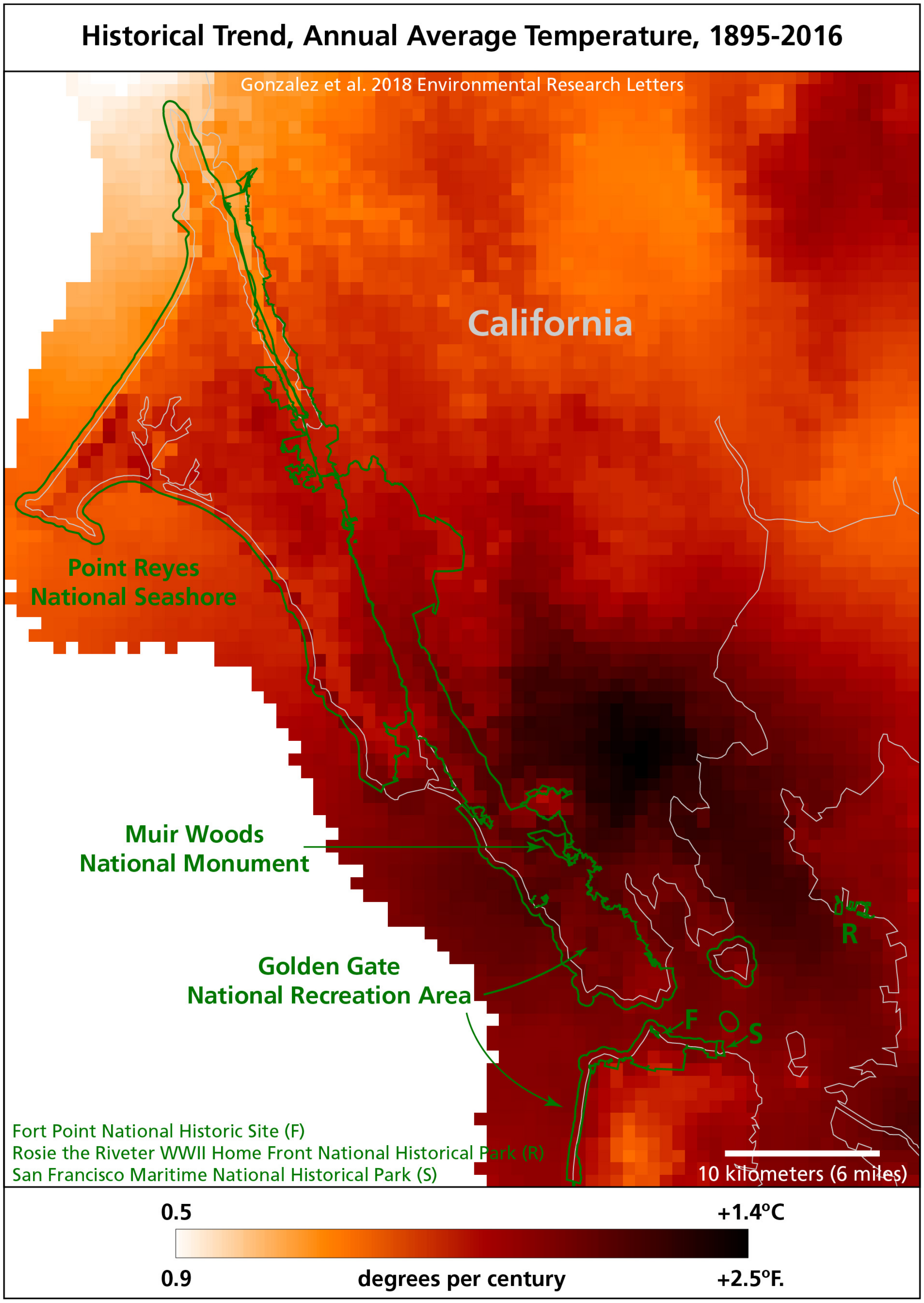

Figure 3. Total annual precipitation, 1895-2016, for the area within Muir Woods National Monument boundaries (Gonzalez et al. 2018).

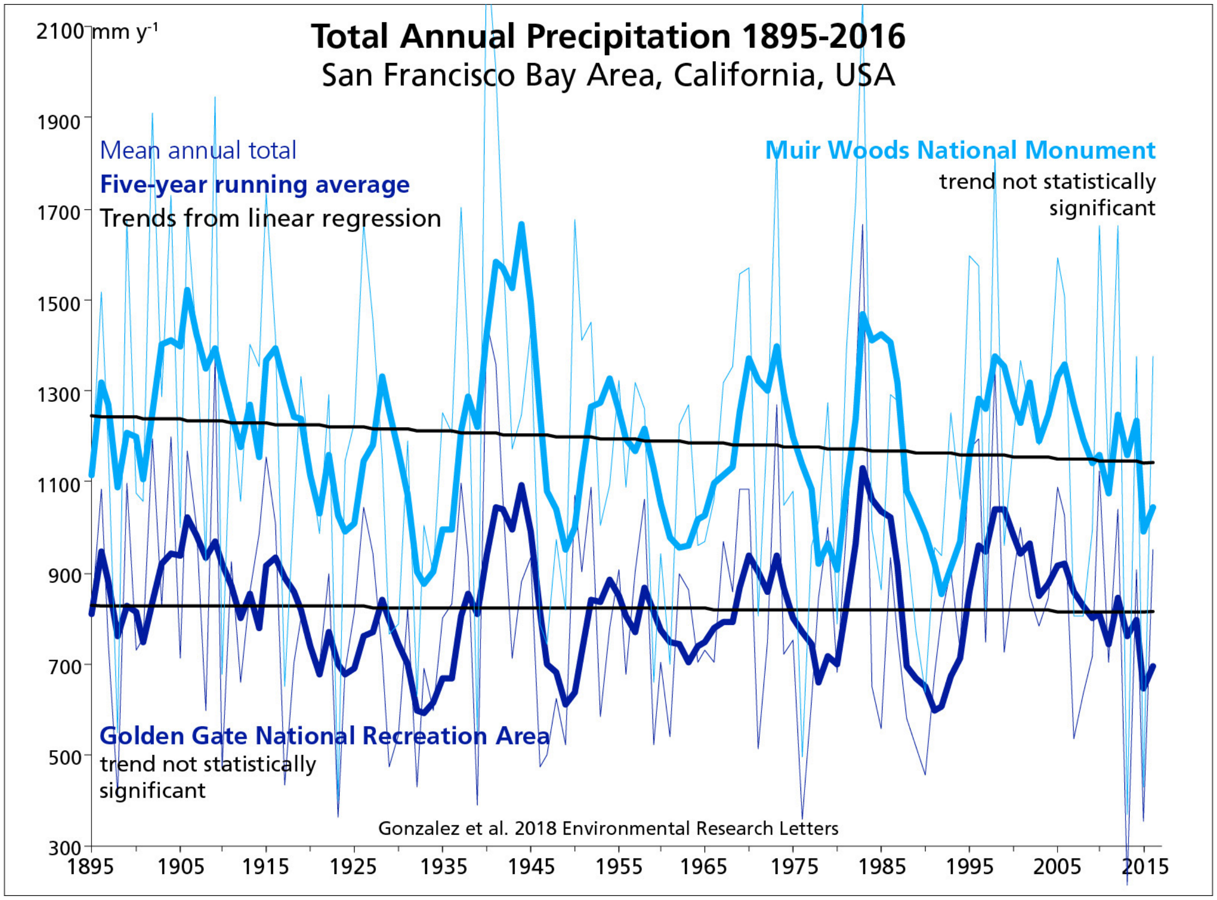

Figure 4. Trend in total annual precipitation, 1895-2016, at 800 m spatial resolution, across Muir Woods National Monument, from linear regression, corrected for temporal autocorrelation (Gonzalez et al. 2018).

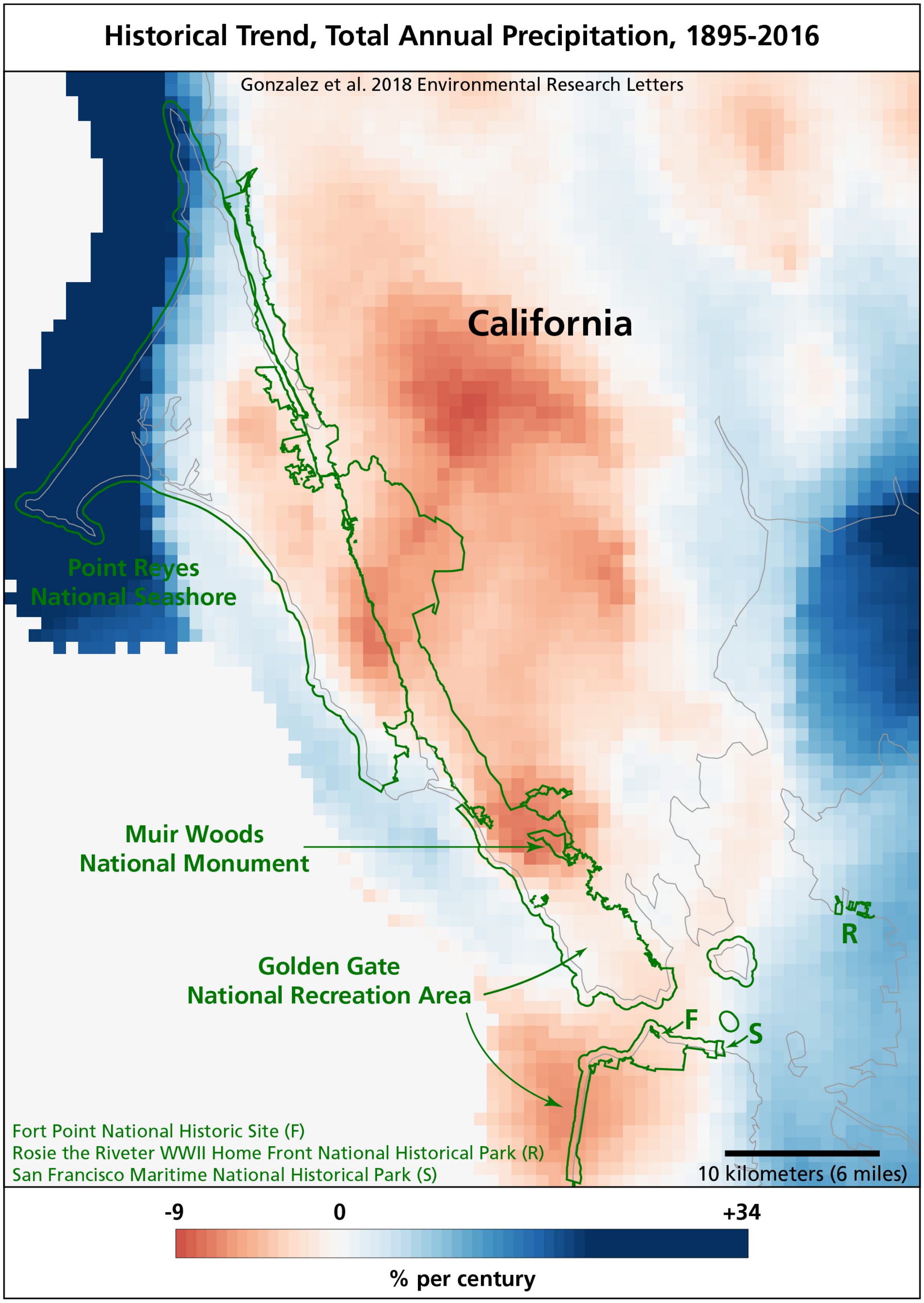

Figure 5. Projections of future climate for the area within park boundaries, relative to 1971-2000 average values (Gonzalez et al. 2018). Each small dot is the output of one of 121 runs of 33 general circulation models. The large color dots are the average values for the four IPCC emissions scenarios. The crosses are the standard deviations of the average values.

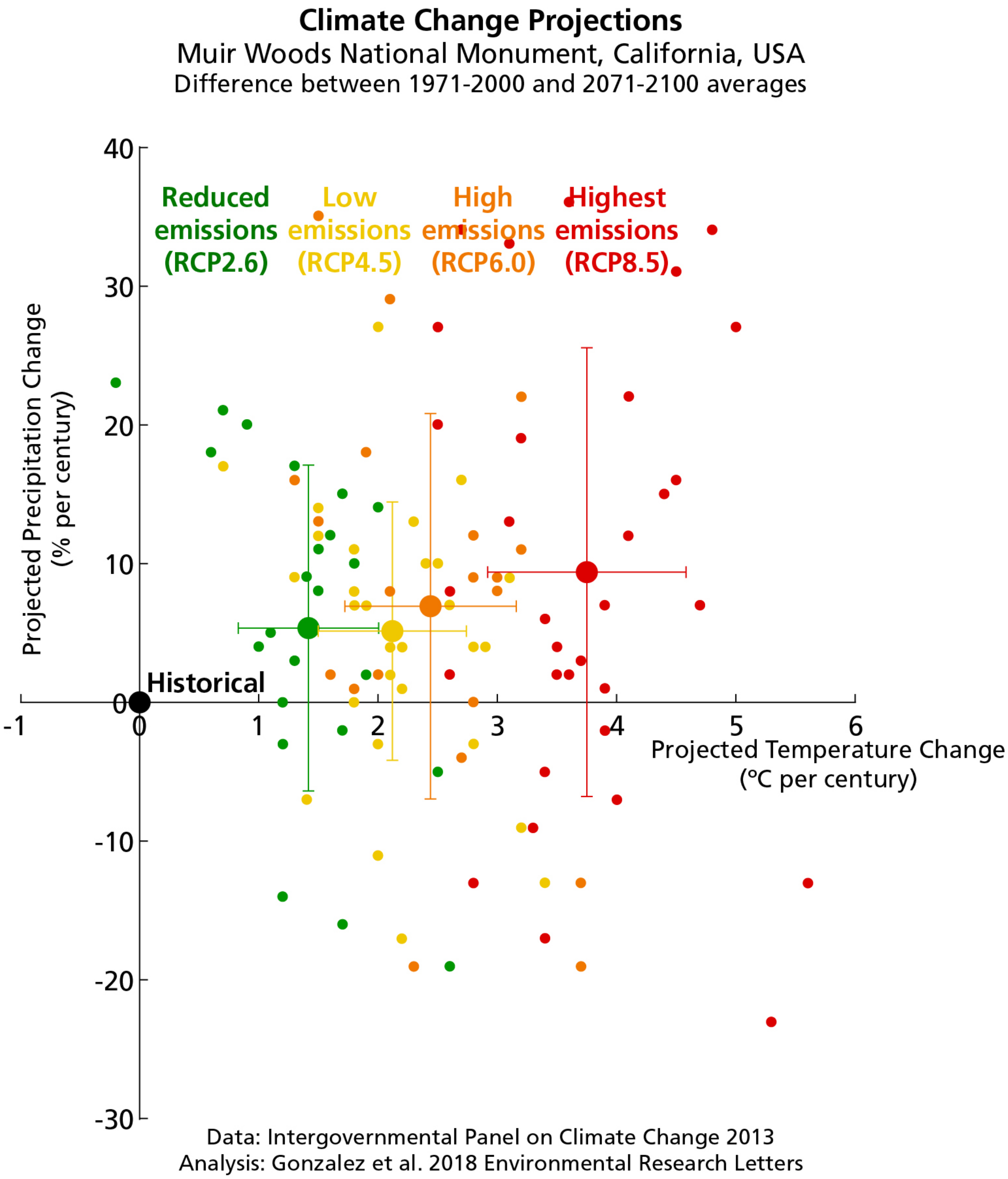

Table 1. **Historical average temperatures** and trends for the area within the boundaries of Muir Woods National Monument (Gonzalez et al. 2018). SD = standard deviation, SE = standard error, sig. = statistical significance, * $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$.

	1971-2000		1895-2010			1950-2010		
	mean	SD	trend	SE	sig.	trend	SE	sig.
	ºC		ºC $century^{-1}$			ºC $century^{-1}$		
Annual	14	0.5	1	0.2	***	1.3	0.5	*
December-February	9.8	0.8	1	0.3	***	1.1	0.5	*
March-May	13.2	0.9	1.1	0.3	***	1.9	0.8	*
June-August	17.4	0.5	0.8	0.2	***	1.7	0.5	**
September-November	15.6	0.7	1.1	0.2	***	0.6	0.5	
January	9.2	1.1	1.2	0.4	**	2.1	0.7	**
February	10.9	1.1	1	0.4	**	0.8	0.8	
March	11.9	1.2	1.1	0.4	**	2.5	0.9	**
April	13.1	1.2	0.7	0.3	*	1.2	0.9	
May	14.7	1.1	1.3	0.3	***	1.9	0.7	*
June	16.7	0.9	0.7	0.3	*	1.6	0.7	*
July	17.5	0.7	0.6	0.2	*	1.5	0.7	*
August	17.9	0.7	1.3	0.3	***	2	0.7	**
September	17.9	1.1	1.3	0.4	***	0.6	0.8	
October	16.3	0.9	1.2	0.3	***	0.8	0.7	
November	12.5	1.2	0.7	0.3	*	0.4	0.7	
December	9.4	1.3	1	0.4	**	0.3	0.9	

Table 2. **Historical average precipitation** totals and trends for the area within the boundaries of Muir Woods National Monument (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	1134	371	-7	9	-2	21
December-February	598	263	-5	13	4	31
March-May	271	148	-15	16	7	40
June-August	16	14	20	27	-47	74
September-November	258	166	-7	19	-23	50
January	226	153	-31	19	-70	44
February	204	146	-8	21	64	49
March	178	143	-26	23	-1	53
April	60	40	15	23	-35	47
May	32	41	-14	30	138	79
June	9	10	-7	36	-35	103
July	3	7	69	78	-11	206
August	5	7	76	48	-92	104
September	15	18	-111	43*	-63	114
October	57	48	6	25	-26	73
November	185	141	-2	24	-19	65
December	158	110	34	23	40	74

Table 3. **Projected temperature increases** (ºC), 2000 to 2100, for the area within the boundaries of Muir Woods National Monument (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	1.4	0.6	2.1	0.6	2.5	0.7	3.8	0.8
December-February	1.4	0.5	2	0.6	2.2	0.7	3.4	0.8
March-May	1.3	0.6	1.8	0.6	2.2	0.6	3.3	0.8
June-August	1.4	0.7	2.2	0.8	2.6	0.8	4	0.9
September-November	1.5	0.7	2.4	0.9	2.7	0.8	4.3	1.2
January	1.4	0.6	2	0.6	2.3	0.7	3.5	0.8
February	1.3	0.6	1.9	0.6	2.2	0.6	3.3	0.7
March	1.3	0.7	1.8	0.6	2.2	0.7	3.2	0.9
April	1.3	0.5	1.7	0.6	2.2	0.6	3.2	0.8
May	1.3	0.6	1.9	0.7	2.3	0.7	3.4	0.8
June	1.4	0.8	2.1	0.9	2.5	0.9	3.7	1
July	1.4	0.8	2.2	0.8	2.7	0.9	3.9	1
August	1.5	0.7	2.4	0.7	2.8	0.8	4.2	0.9
September	1.7	0.8	2.6	0.8	2.9	1	4.5	1.1
October	1.5	0.8	2.5	1	2.7	0.9	4.4	1.3
November	1.4	0.6	2.3	1.1	2.5	0.8	4	1.4
December	1.4	0.5	2.1	0.9	2.2	0.7	3.6	1.1

Table 4. **Projected precipitation changes** (%), 2000 to 2100, for the area within the boundaries of Muir Woods National Monument (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	5	12	5	9	7	14	9	16
December-February	7	15	10	14	13	19	19	22
March-May	7	16	2	20	2	12	2	26
June-August	23	35	30	62	12	36	38	77
September-November	-2	14	-6	24	-6	19	-12	24
January	9	20	14	20	12	22	23	26
February	7	22	14	24	19	30	27	37
March	7	20	4	20	8	16	8	24
April	8	25	0	25	-6	20	-6	37
May	14	37	2	49	-8	29	-11	48
June	7	35	-7	37	-14	31	-9	44
July	108	252	154	260	157	253	199	342
August	66	114	92	139	51	88	108	144
September	10	61	10	68	4	41	20	82
October	7	32	-8	26	-2	34	-16	32
November	-6	13	-6	28	-9	18	-13	29
December	6	23	4	23	13	25	9	24

References

Abatzoglou, J.T. and A. Park Williams. 2016. Impact of anthropogenic climate change on wildfire across western US forests. Proceedings of the National Academy of Sciences of the USA 113(42): 11770-11775.

Ackerly, D.D., W.K. Cornwell, S.B. Weiss, L.E. Flint, and A.L. Flint. 2015. A Geographic Mosaic of Climate Change Impacts on Terrestrial Vegetation: Which Areas Are Most at Risk? PLoS ONE 10(6): e0130629. doi:10.1371/journal.pone.0130629.

Baker, T.R., O.L. Phillips, Y. Malhi, S. Almeida, L. Arroyo, A. Di Fiore, T. Erwin, N. Higuchi, T.J. Kileen, S.G. Laurance, W.F. Laurance, S.L. Lewis, A. Monteagudo, D.A. Neill, P.N. Vargas, N.C.A. Pitman, J.N.M. Silva, and R.V. Martinez. 2004. Increasing biomass in Amazonian forest plots. Philosophical Transactions of the Royal Society of London B 359: 353-365.

Barron, J.A., L. Heusser, T. Herbert, and M. Lyle. 2003. High-resolution climatic evolution of coastal northern California during the past 16,000 years. Paleoceanography 18(1): 1-20. doi:10.1029/2002PA000768.

Bolsinger, C.L. and K.L. Waddell. 1993. Area of Old-Growth Forests in California, Oregon, and Washington. PNW-RB-197. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 26 pages.

Brown, P.M., M.W. Kaye, and D. Buckley. 1999. Fire history in Douglas-fir and coast redwood forests at Point Reyes National Seashore, California. Northwest Science 73: 205-216.

Brown, P.M. and W.T. Baxter. 2003. Fire History in Coast Redwood Forests of the Mendocino Coast, California. Northwest Science. 77(2): 147-158.

Burgess, S.S.O. and T.E. Dawson. 2004. The contribution of fog to the water relations of *Sequoia sempervirens* (D. Don): foliar uptake and prevention of dehydration. Plant, Cell and Environment 27, 1023-1034.

Carroll, A.L., S.C. Sillett, and R.D. Kramer. 2014. Millenium-Scale Crossdating and Inter-Annual Climate Sensitivities of Standing California Redwoods. PLoS ONE 9(7): e102545, doi:10.1371/journal.pone.0102545.

Cheung, W.W.L., R.D. Brodeur, T.A. Okey, and D. Pauly. 2015. Projecting future changes in distributions of pelagic fish species of Northeast Pacific shelf seas. Progress in Oceanography 130: 19-31.

Church, J.A. and N.J. White. 2011. Sea-level rise from the late 19th to the early 21st Century. Surveys in Geophysics 32: 585-602.

Cook, B.I., T.R. Ault, and J.E. Smerdon. 2015. Unprecedented 21st century drought risk in the American Southwest and Central Plains. Science Advances 1(1): e1400082. DOI: 10.1126/sciadv.1400082.

Crozier, L.G., M.M. McClure, T. Beechie, S.J. Bograd, D.A. Boughton, M. Carr, T.D. Cooney, J.B. Dunham, C.M. Greene, M.A. Haltuch, E.L. Hazen, D.M. Holzer, D.D. Huff, R.C. Johnson, C.E. Jordan, I.C. Kaplan, S.T. Lindley, N.J. Mantua, P.B. Moyle, J.M. Meyers, M.W. Nelson, B.C. Spence, L.A. Weitkamp, T.H. Williams, and E. Willis-Norton. 2019. Climatic vulnerability assessment for Pacific salmon and steelhead in the California Current Large Marine Ecosystem. PLoS ONE 14(7): e0217711, https://doi.org/10.1371/journal.pone.0217711.

Dawson, T.E. 1998. Fog in the California redwood forest: ecosystem inputs and use by plants. Oecologia 117:476-485.

Deitch, M.J., M. Van Docto, M. Obedzinski, S.P. Nossaman, and A. Bartshire. 2018. Impact of multi-annual drought on streamflow and habitat in coastal California salmonid streams. Hydrological Sciences Journal 63(8): 1219-1235.

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(13): 3931-3936.

Dorman, C.E., J. Mejia, D. Koračin, and D. McEvoy. 2017. Worldwide Marine Fog Occurrence and Climatology. In: D. Koračin D. and C. Dorman (eds) Marine Fog: Challenges and Advancements in Observations, Modeling, and Forecasting. Springer Atmospheric Sciences. Springer, Cham. https://doi-org.libproxy.berkeley.edu/10.1007/978-3-319-45229-6_2

Easterling, D.R., K.E. Kunkel, J.R. Arnold, T. Knutson, A.N. LeGrande, L.R. Leung, R.S. Vose, D.E. Waliser, and M.F. Wehner. 2017. Precipitation change in the United States. In: Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)*Climate Science Special Report*: Fourth National Climate Assessment, Volume I. U.S. Global Change Research Program, Washington, DC, USA, pp. 207-230, doi: 10.7930/J0H993CC.

Edson, E., S. Farrell, A. Fish, T. Gardali, J. Klein, W. Kuhn, W. Merkle, M. O'Herron, and A. Williams. 2016. Measuring the Health of a Mountain: A Report on Mount Tamalpais' Natural Resources. Available at: https://www.onetam.org/media/pdfs/peak-health-white- paper-2016.pdf

Fernandez, M, H.H. Hamilton, and L.M. Kueppers. 2015. Back to the future: using historical climate variation to project near-term shifts in habitat suitable for coast redwood. Global Change Biology 21, 4141-4152, doi: 10.1111/gcb.13027.

Forrestel, A.B., B.S. Ramage, T. Moody, M.A. Moritz, and S.L. Stephens. 2015. Disease, fuels and potential fire behavior: Impacts of Sudden Oak Death in two coastal California forest types. Forest Ecology and Management 348: 23-30.

Francis, E.J., G.P. Asner, K.J. Mach, and C.B. Field. 2020. Landscape scale variation in the hydrologic niche of California coast redwood. Ecography 43: 1305-1315.

Golden Gate National Recreation Area (GGNRA). 2005. Chapter 3 "Affected Environment" in: "Fire Management Plan Final Environmental Impact Statement." 63 pages.

Golden Gate National Recreation Area (GGNRA). 2015. "Reference Document for the Fire Management Plan." 392 pages.

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. 2016. Climate Change in the National Parks of the San Francisco Bay Area, California, USA. National Park Service, U.S. Department of the Interior. 54 pages.

Gonzalez, P., F. Wang, M. Notaro, D.J. Vimont, and J.W. Williams. 2018. Disproportionate magnitude of climate change in United States national parks. Environmental Research Letters 13: 104001, doi.org/10.1088/1748-9326/aade09.

Goss, M., D.L. Swain, J.T. Abatzoglou, A. Sarhadi, C.A. Kolden, A. Park Williams, and N.S. Diffenbaugh. 2020. Climate change is increasing the likelihood of extreme autumn wildfire conditions across California. Environmental Research Letters 15: 094016, doi.org/10.1088/1748-9326/ab83a7.

Holden, Z.A., A. Swanson, C.H. Luce, W.M. Jolly, M. Maneta, J.W. Oyler, D.A. Warren, R. Parsons, and D. Affleck. 2018. Decreasing fire season precipitation increased recent western US forest wildfire activity. Proceedings of the National Academy of Sciences of the USA 115(36): E8349-E8357.

IEA Atlas of Energy. 2020. "CO2 Emissions from Fuel Combustion." Located at: http://energyatlas.iea.org/#!/tellmap/1378539487/4. Accessed November 7, 2020.

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). 2018. Summary for Policymakers. In: Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)

Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. World Meteorological Organization, Geneva, Switzerland. 32 pages.

Johnstone, J.A. and T.E. Dawson. 2010. Climatic context and ecological implications of summer fog decline in the coast redwood region. Proceedings of the National Academy of Sciences of the USA 107(10): 4533-4538.

Katz, J., P.B. Moyle, R.M. Quiñones, J. Israel, and S. Purdy. 2013. Impending extinction of salmon, steelhead, and trout (Salmonidae) in California. Environ Biol Fish 96:1169-1186. DOI 10.1007/s10641-012-9974-8.

Kawai, H., T. Koshiro, H. Endo, and O. Arakawa. 2018. Changes in Marine Fog Over the North Pacific Under Different Climates in CMIP5 Multimodel Simulations. Journal of Geophysical Research: Atmospheres 123: 10,911-10,924. https://doi.org/10.1029/2018JD028899.

Knapp, P.A., and P.T. Soule. 2017. Spatio-Temporal Linkages between Declining Arctic Sea-Ice Extent and Increasing Wildfire Activity in the Western United States. Forests 8, 313; doi:10.3390/f8090313.

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

Metz, M.R., J.M. Varner, K.M. Frangioso, R.K. Meentemeyer, and D.M. Rizzo. 2013. Unexpected redwood mortality from synergies between wildfire and an emerging infectious disease. Ecology 94(10): 2152-2159.

Micheli, E., L. Flint, S. Veloz, K. Johnson, and N. Heller. 2016. Climate Ready North Bay Vulnerability Assessment Data Products: 2. Marin Municipal Water District User Group. A technical memorandum prepared by the Dwight Center for Conservation Science at Pepperwood, Santa Rosa, CA, for the California Coastal Conservancy and Regional Climate Protection Authority, 33 pp. Available at: http://climate.calcommons.org/crnb/mmwd.

National Park Service (NPS). 2016. Golden Gate National Recreation Area: 2016 Climate Change Action Plan. Climate Friendly Parks. 41 pages. Located at: https://www.nps.gov/goga/learn/nature/upload/2016-Climate-Change-Action-Plan-1.pdf.

National Park Service (NPS). 2017. Listing of Acreage (Summary). Land Resources National Program Division. 15 pages.

National Park Service (NPS). 2019. "Redwood Creek Salmon Habitat Enrichment Project." Located at: https://www.nps.gov/articles/redwood-creek-salmon-habitat-enhancement.htm. Accessed November 1, 2020.

National Park Service (NPS). 2020. "Becoming a Carbon Neutral Park." Located at: https://www.nps.gov/goga/learn/nature/carbon-neutral-park.htm. Accessed January 4, 2021.

Noss, R.F. 2000. The Redwood Forest: History, Ecology, and Conservation of the Coast Redwoods. Island Press.

Osterback, A.M.K., C.H. Kern, E.A. Kanawi, J.M. Perez, and J.D. Kiernan. 2018. The effects of early sandbar formation on the abundance and ecology of coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*Oncorhynchus mykiss*) in a central California coastal lagoon.Canadian Journal of Fisheries & Aquatic Sciences 75: 2184-2197.

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 heterogenous climate change in California. Global Change Biology 20: 2841-2855, doi: 10.1111/gcb.12638.

Schaff, C.J., S.J. Kelson, S.C. Nussle, and S.M. Carlson. 2017. Black spot infection in juvenile steelhead trout increases with stream temperature in northern California. Environmental Biology of Fishes 100:733-744, DOI 10.1007/s10641-017-0599-9.

Soroye, P., T. Newbold, and J. Kerr. 2020. Climate change contributes to widespread declines among bumble bees across continents. Science 367(6478): 685-688.

Stephens S.L. and D.L. Fry. 2005. Fire History in Coast Redwood Stands in the Northeastern Santa Cruz Mountains, California. *Fire Ecology* 1:2-19.

Torregrosa, A., L.E. Flint, and A.L. Flint. 2020. Hydrologic Resilience from Summertime Fog and Recharge: A Case Study for Coho Salmon Recovery Planning. Journal of the American Water Resources Association 56(1): 134-160.

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, doi:10.1002/2015GL064924.

Williams, A.P., E.R. Cook, J.E. Smerdon, B.I. Cook, J.T. Abatzoglou, K. Bolles, S.H. Baek, A.M. Badger, and B. Livneh. 2020. Large contribution from anthropogenic warming to an emerging North American megadrought. Science 368: 314-318, doi:10.1126/science.aaz9600.

Wynes, S. and K.A. Nicholas. 2017. The climate mitigation gap: education and government recommendations miss the most effective individual actions. Environ. Res. Lett. 12: 074024.

Van Pelt, R., S.C. Sillett, W.A. Kruse, J.A. Freund, and R.D. Kramer. 2016. Emergent crowns and light-use complementarity lead to global maximum biomass and leaf area in *Sequoia sempervirens* forests. Forest Ecology and Management 375: 279-308.

Voelker, S.L, J.S. Roden, and T.E. Dawson. 2018. Millennial-scale tree-ring isotope chronologies from coast redwoods provide insights on controls over California hydroclimate variability. Oecologica 187: 897-909, https://doi.org/10.1007/s00442-018-4193-4.

Vose, R.S., D.R. Easterling, K.E. Kunkel, A.N. LeGrande, and M.F. Wehner. 2017. Temperature changes in the United States. In: Climate Science Special Report: Fourth National Climate Assessment, Volume I. Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.). U.S. Global Change Research Program, Washington, DC, USA, pp. 185-206, doi: 10.7930/J0N29V45.