Human-caused climate change in United States national parks and solutions for the future

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Conflict of interest declaration. The author declares that he has no conflict of interest to disclose.

Disclaimer. This publication represents the views of the author and does not necessarily represent the views of the US Government.

Abstract

Human-caused climate change has exposed the US national park area to more severe increases in heat and aridity than the country as a whole and caused widespread impacts on ecosystems and resources. Reducing carbon dioxide emissions from cars, power plants, and other human sources would reduce future risks. Since 1895, annual average temperature of the area of the 419 national parks has increased at a rate of 1.0 ± 0.2°C (1.8 ± 0.4°F) per century, double the rate of the US as a whole, while precipitation has declined significantly on 12% of national park area, compared with 3% of the US. This occurs because extensive areas of national parks are located in extreme environments. Scientific research in national parks has detected numerous changes that analyses have attributed primarily to human-caused climate change. These include a doubling of the area burned by wildfire across the western US, including Yosemite National Park, melting of glaciers in Glacier Bay National Park, a doubling of tree mortality across the western US, including Sequoia National Park, a loss of bird species from Death Valley National Park, a shift of trees onto tundra in Noatak National Preserve, sea level rise of 42 cm (17 in.) near the Statue of Liberty National Monument, and other impacts. Without emissions reductions, climate change could increase temperatures across the national parks, up to 9°C (16°F) by 2100 in parks in Alaska. This could melt all glaciers from Glacier National Park, raise sea level enough to inundate half of Everglades National Park, dissolve coral reefs in Virgin Islands National Park through ocean acidification, and damage many other natural and cultural resources. Adaptation measures, including conservation of refugia in Joshua Tree National Park and raising heat-resistant local corals in Biscayne National Park, can strengthen ecosystem integrity. Yet, reducing greenhouse gas emissions from human activities is the only solution that prevents the pollution that causes climate change. Energy conservation and efficiency improvements, renewable energy, public transit, and other actions could lower projected heating by two-thirds, reducing risks to our national parks.

Introduction

Human emissions of greenhouse gases have increased global temperature 0.9° ± 0.1°C (1.6 ± 0.2°F) from 1850 to 2015 (IPCC 2013, 2019a), causing glacial melt (Marzeion et al. 2014), wildfire increases (Abtazoglou and Williams 2016), biome shifts (Gonzalez et al. 2010), plant and animal range shifts (Chen et al. 2011), and other impacts globally (IPCC 2014). Continued climate change increases future risks of plant and animal extinctions (Urban 2015), severe tree mortality (McDowell et al. 2016), invasive species increases (Early et al. 2016), and other damage to ecosystems and human well-being (IPCC 2014, 2018, 2019a, 2019b).

Spatial analyses of historical climate trends show that anthropogenic (human-caused) climate change has caused significant heat and aridity increases across the US national parks (Gonzalez et al. 2018) and wide-spread physical and ecological impacts (Gonzalez 2017). Without reductions of emissions of carbon dioxide (CO_2), the main greenhouse gas, from cars, power plants, deforestation, and other human sources, continued climate change could further heat the parks (Gonzalez et al. 2018) and increase future risks (Gonzalez 2017).

This article presents a scientific assessment of human-caused climate change in the 419 US national parks. Methods include: synthesis of published spatial analyses of historical and projected climate trends; systematic searches of published scientific research in the Clarivate Analytics Web of Science, the authoritative database of scientific literature, for research on climate change that used data from US national parks; evaluation of whether research on historical changes detected changes statistically significantly different from natural variation and attributed those changes more to human-caused climate change than other factors; identification of field adaptation measures and carbon solutions implemented in parks and published in the scientific literature; and evaluation of common patterns among published results.

The objectives of this article are to: (1) synthesize the most robust scientific information on human-caused climate change in the US national parks, (2) produce a comprehensive survey that informs decisions for the national park system as a whole, and (3) provide park-specific details that inform resource management in individual national parks.

Historical impacts in US national parks

The first spatial analysis of temperature and precipitation trends across all the US national parks revealed that human-caused climate change has exposed the national park area to more severe increases in heat and aridity than the country as a whole (Gonzalez et al. 2018). Average annual temperature of the area of the 419 national parks increased at a rate of 1 ± 0.2°C (1.8 ± 0.4°F) per century from 1895 to 2010, double the national rate (Table 1, Figure 1). Total annual precipitation of the national park area declined, but the change was not statistically significant, while the measure showed a statistically significant increase for the US as a whole (Table 1). Precipitation decreased across a greater fraction of the national park area (12%) than the country as a whole (3%) (Figure 1). The disproportionate exposure of the US national parks to the increased heat and aridity of climate change occurred because extensive areas of the parks are located in extreme environments—the Arctic (parks 19%, US 3%), high mountains (elevation >2500 m [8200 ft]) (parks 5%, US 2%), and the arid southwestern US.

Out of all 419 national parks, annual average temperature from 1950 to 2010 increased at the highest rate in Denali National Preserve (analyzed separately from Denali National Park), Alaska, 4.3°C (~8°F) per century,

TABLE 1. Climate change trends across the US national parks and the US as a whole (Gonzalez et al. 2018). Historical trends and standard errors from linear regression, corrected for temporal autocorrelation. Historical period for areas outside the contiguous states is 1901–2009, the period of available spatial data. Updated trends for the contiguous 48 states for 1895–2017: US 48, 0.4 ± 0.1°C per century**, 7 ± 2% per century***; national parks 48, 0.8 ± 0.1°C per century***, 5 ± 2% per century*. Historical precipitation trends are relative to the average of the entire period. Projected changes and standard deviations are for the difference between the periods 1971–2000 and 2071–2100, from all climate model output available from IPCC (2013). Emissions scenarios: RCP2.6 – reduced emissions, RCP8.5 – highest emissions. Statistical significance: * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001.

	Area	1895–2010 Temperature	Precipitation	2000–2100 Temperature		Precipitation	
				RCP2.6	RCP8.5	RCP2.6	RCP8.5
	km²	°C per century	% per century	°C per century		% per century	
National Park System							
Contiguous 48 states	130,000	0.6 ± 0.1 ***	4 ± 2	1.6 ± 0.7	4.9 ± 1	6 ± 8	7 ± 17
Alaska	220,000	1.2 ± 0.3 ***	−7 ± 3 *	2.5 ± 1.1	6.6 ± 1.5	11 ± 7	30 ± 11
Hawaii	1,800	1.3 ± 0.1 ***	−7 ± 6	1.1 ± 0.4	3.2 ± 0.8	1 ± 260	12 ± 51
Puerto Rico, Virgin Islands	39	1.4 ± 0.1 ***	−8 ± 5	1 ± 0.4	2.9 ± 0.6	−0.1 ± 10	−22 ± 25
Guam	5	0.2 ± 0.05 ***	−1 ± 5	1 ± 0.3	3 ± 0.6	6 ± 15	19 ± 32
American Samoa	13	1.4 ± 0.1 ***	5 ± 5	0.9 ± 0.3	2.7 ± 0.6	−1 ± 17	3 ± 24
National Park System	360,000	1.0 ± 0.2 ***	−4 ± 2	2.2 ± 0.9	5.9 ± 1.3	9 ± 9	21 ± 14
United States	9,300,000	0.4 ± 0.1 **	4 ± 2 *	1.8 ± 0.8	5.3 ± 1.2	6 ± 8	11 ± 22
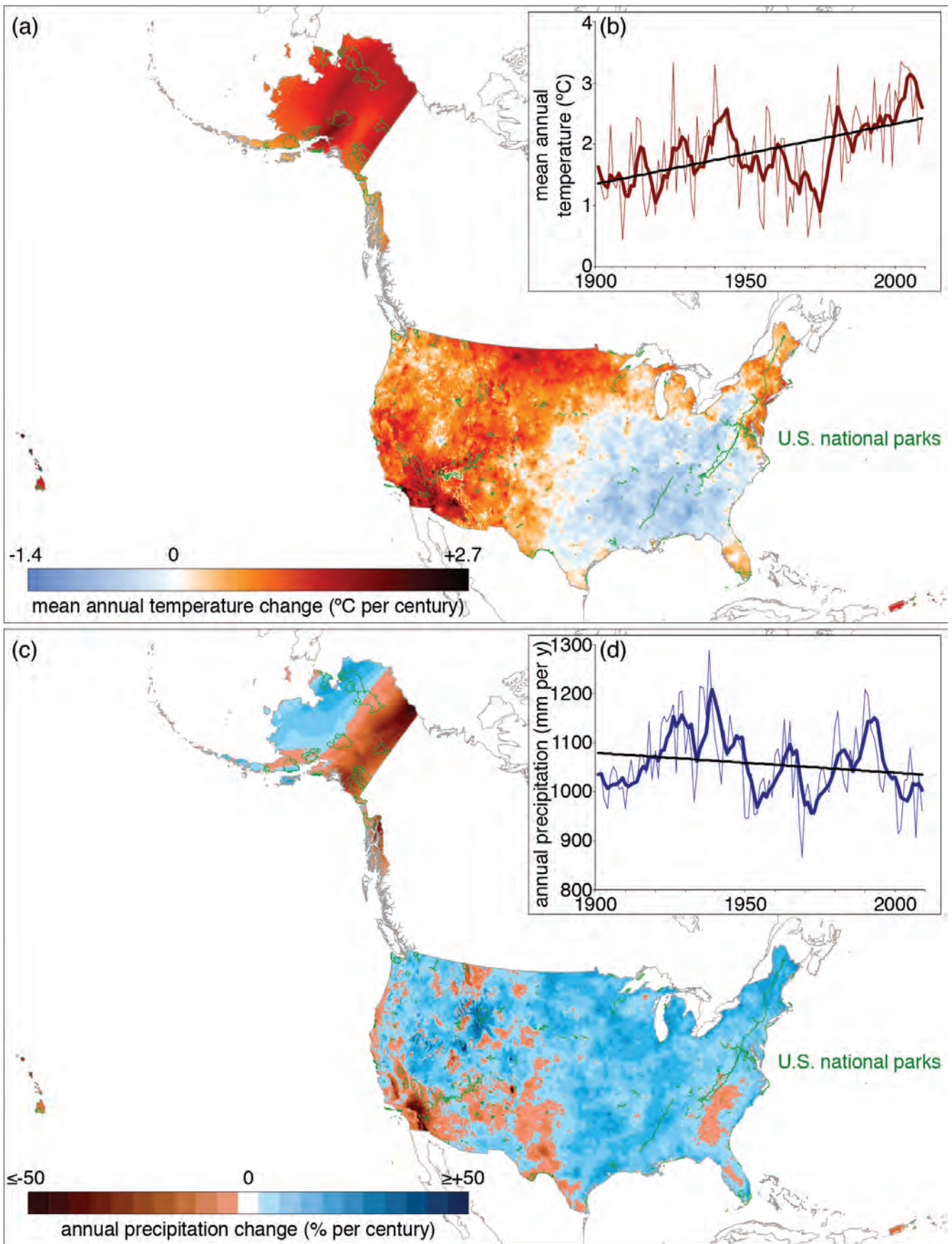
FIGURE 1. Historical climate change, 1895–2010 (Gonzalez et al. 2018). (a) Mean annual temperature change (ºC per century). (b) Mean annual temperature (ºC) of the national park area, annual values (thin line), five-year running average (thick line), and trend from linear regression, corrected for temporal autocorrelation (straight line; trend statistically significant, P <0.0001). (c) Annual precipitation changes (% per century), relative to the 1895–2010 average. (d) Average annual precipitation (mm per year) of the national park area (trend not statistically significant).

and rainfall declined most in Honouliuli National Historic Site, Hawaii, –85% per century. Seasonal average temperatures in national parks increased most in the contiguous 48 states, Hawai'i, and the Caribbean, in summer; and in Alaska, American Samoa, and Guam, in winter. Spatial data and results for each national park are publicly available at http://gif.berkeley.edu/resources/anthropogenic_climate_change.html.

Published field research from national parks has contributed to the detection of 20th-century physical and ecological changes and their attribution more to human-caused climate change than other factors. *Detection* is the finding of statistically significant changes over time that are different than natural variation (IPCC 2018). *Attribution* is the analysis and determination of relative contributions of human and natural causes of the detected changes (IPCC 2018). Building on the first comprehensive assessment of published climate change impacts in US national parks (Gonzalez 2017), historical changes detected and attributed to human-caused climate change in US national parks include the following.

Glacial melt. Human-caused climate change has caused two-thirds of the melting of 168,000 glaciers globally since 1991 (Marzeion et al. 2014, IPCC 2019b), including Muir Glacier in Glacier Bay NP, which melted up to 640 meters (2100 ft) in depth from 1948 to 2000 (Larsen et al. 2007) (Figure 2); Agassiz Glacier, in Glacier NP, which melted 1.5 km (1 mi) in length from 1926 to 1979 (Pederson et al. 2004); numerous glaciers in North Cascades NP and the surrounding area, which in total declined 7% in surface area from 1958 to 1998 (Fountain et al. 2009); and four glaciers in North Cascades NP that completely melted by 2004 (Pelto 2006).

Snow cover reduction. Across the western US, including sites in 11 national parks, climate change has reduced snowpack to its lowest level in 800 years (Pederson et al. 2011). Climate change caused half of the reduction in snowpack from 1950 to 1999 in the western US, including at snow measurement sites in numerous national parks (Pierce et al. 2008). In Gates of the Arctic NP and Preserve, the area of perennial snowfields contracted 3% from 1985 to 2017 (Tedesche et al. 2019), part of an overall reduction since 1922 of snow cover across the Northern Hemisphere attributed to climate change (Rupp et al. 2013).

Drought. National parks in the southwestern US have experienced severe droughts detected, in part, from weather station measurements in national parks and driven, in part, by human-caused climate change.

Across the southwestern US, the increased heat and aridity of human-caused climate change account for half the magnitude of a regional drought from 2000 to the present that has been the most severe drought since the 1500s, reducing soil moisture to its lowest levels since that time (Williams et al. 2020). In California, the most severe drought in a century of weather station measurements occurred from 2012 to 2016, caused by the hottest annual average temperature in the period 1896–2014 and near-record low rainfall and snowfall (Diffenbaugh et al. 2015). The high temperatures of climate change accounted for one-tenth to one-fifth of the magnitude of the California drought (Williams et al. 2015). In the Colorado River Basin, the high temperatures of climate change have combined with low rainfall and snowfall to cause a drought from 2000 to the present that is the most severe since the start of weather station measurements in 1906 (Udall and Overpeck 2017; Xiao et al. 2018).

FIGURE 2. Muir Glacier, Glacier Bay NP on August 13, 1941 (photo William O. Field, courtesy of the National Park Service, National Snow and Ice Data Center, and US Geological Survey) and on August 31, 2004 (photo Bruce F. Molina, courtesy US Geological Survey). Photos aligned by P. Gonzalez. From 1948 to 2000, climate change melted 640 m in depth from Muir Glacier at its lowest extent (Larsen et al. 2007; Marzeion et al. 2014).

Colorado River flow decline. Climate change has caused half of a 16% decline from 1916 to 2014 of the flow of the Colorado River, which runs through Arches NP, Canyonlands NP, Glen Canyon National Recreation Area (NRA), Grand Canyon NP, and Lake Mead NRA (Udall and Overpeck 2017; Xiao et al. 2018). The combination of water withdrawals for agriculture and cities and drought reduced Lakes Mead and Powell in 2016 to their lowest levels since they were filled after the damming of the river (Xiao et al. 2018).

Wildfire increase. Wildfire is a natural part of many ecosystems but excessive wildfire can damage them and kill people. For the western US as a whole, including Yosemite NP and numerous other national parks, climate change doubled the area burned by wildfire from 1984 to 2015, compared with the area of natural burning (Abatzoglou and Williams 2016). The hotter temperatures of climate change combined with a statistically significant 12% decrease of summer rainfall from 1984 to 2016 to contribute to a nine-fold increase of burned area across the western US, including numerous national parks (Holden et al. 2018). In the most strictly protected areas of Canada and the US, climate

factors (temperature, precipitation, relative humidity, evapotranspiration) explained the majority of burned area from 1984 to 2014, outweighing local human factors (population density, roads, and built area) (Mansuy et al. 2019).

Tree mortality. Across the western US, including sites in Kings Canyon, Lassen Volcanic, Mount Rainier, Rocky Mountain, Sequoia, and Yosemite National Parks, climate change doubled tree mortality from 1955 to 2007 (van Mantgem et al. 2009), due to drought, the most extensive bark beetle infestations in a century, and increased wildfire (Raffa et al. 2008; van Mantgem et al. 2009; Berner et al. 2017) (Figure 3). In Sequoia NP and across the Sierra Nevada, subsurface moisture exhaustion and soil drying due to climate change increased tree mortality during the California drought by one-quarter over the 1984–2015 average (Goulden and Bales 2019). In plots in Sequoia NP, nearly one-quarter of trees died during the California drought, with mortality rates of ponderosa pine (*Pinus ponderosa*) and sugar pine (*Pinus lambertiana*) increasing up to seven times the mortality of the non-drought period of 2004–2007 (Stephenson et al. 2019). In Yellowstone NP and

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FIGURE 3. Dead lodgepole pines (*Pinus contorta*) in Rocky Mountain NP. Climate change doubled tree mortality across the western US, in a sample that included sites in the park, from 1955 to 2007 (van Mantgem et al. 2009).

the surrounding ecosystem, bark beetle outbreaks due to the hotter temperatures of climate change have caused mortality of half the area of whitebark pine (*Pinus albicaulis*) (Macfarlane et al. 2013; Raffa et al. 2013).

Biome shifts. By moving warmer conditions upslope and farther north, climate change has shifted biomes (major vegetation types) at sites around the world, including in at least two US national parks (Gonzalez et al. 2010). In Yosemite NP, climate change shifted subalpine forest upslope into subalpine meadows between 1880 and 2002 (Millar et al. 2004; Lubetkin et al. 2017). In Noatak National Preserve, climate change shifted boreal conifer forest northward onto formerly treeless tundra between 1800 and 1990 (Suarez et al. 1999).

Sea level rise. Tidal gauges have detected significant increases in sea level in or near national parks: 33 cm (13 in.) since 1854 in Golden Gate NRA, San Francisco, California, which hosts the tidal gauge with the longest time series in the Western Hemisphere (Slangen et al. 2016; NOAA 2019a); 42 cm (17 in.) since 1856 at New York City (NOAA 2019b), near the Statue of Liberty National Monument; and 32 cm (13 in.) since 1924 at Washington, DC (NOAA 2019c), near the Jefferson Memorial and other national parks. Sea level rises as meltwater from glaciers and other land ice runs into the ocean and as water expands as it warms, phenomena that are caused by climate change (Slangen et al. 2016).

Ocean warming. Measurements of sea surface temperature from ships and buoys around the world, many offshore from US national parks, have detected a global average increase of $0.7 \pm 0.1°C$ ($1.3 \pm 0.2°F$) from 1900 to 2016 (Huang et al. 2017; Kennedy et al. 2019) and analyses of causal factors attributed this to human-caused climate change (IPCC 2013, 2019b). Temperatures in the California Current of the Pacific Ocean, off the coast of Channel Islands NP, Point Reyes National Seashore, and other parks, increased $0.8 \pm 0.2°C$ ($1.4 \pm 0.4°F$) from 1920 to 2016 (Rayner et al. 2006; Jacox et al. 2018).

Coral bleaching. The hotter ocean temperatures of climate change bleached and killed corals in the National Park of American Samoa in 2015 and 2017 (Hughes et al. 2018; Morikawa and Palumbi 2019; Thomas et al. 2019). Climate change bleached and killed up to 80% of coral reef area at sites in Biscayne NP, Buck Island Reef National Monument, Salt River Bay National Historical Park and Ecological Preserve, Virgin Islands NP, and Virgin Islands Coral Reef National Monument in 2005 (Eakin et al. 2010; Welle et al. 2017).

Ocean acidification. Increased atmospheric CO_2 concentrations from human activities are raising the acidity of ocean water as the CO_2 dissolves in the water and forms carbonic acid. Analyses of water across the Pacific Ocean, including off the coast of Cabrillo National Monument, show that CO_2 from human sources increased acidity 25%–40% (–0.10 to –0.15 pH) between the preindustrial era (ca. 1750) and the 2000s (Gruber et al. 2012; Carter et al. 2017). Along the Pacific coast, including sites off the coast of Olympic NP and Redwood NP, ocean acidification has dissolved shells of pteropods (small planktonic sea snails) (Busch et al. 2014; Feely et al. 2016; Bednaršek et al. 2017).

Bird species losses. In Death Valley NP, Joshua Tree NP, Mojave National Preserve, and adjacent federal lands, field research detected an average net loss of 18 bird species (43% of bird species richness) between the periods 1908–1968 and 2013–2016 (Iknayan and Beissinger 2018). Analyses of potential causal factors, including climate, fire, and grazing, attributed the loss to reduced water supplies from a decline in precipitation due to climate change (Iknayan and Beissinger 2018). The lack of water caused birds to overheat (Riddell et al. 2019).

Wildlife shifts. In Yosemite NP, field research found that climate change shifted the ranges of the pika (*Ochotona princeps*) and other small mammal species 500 meters (~1600 ft) upslope from 1920 to 2006, a period in which temperature increased 3°C (~5°F) (Moritz et al. 2008). Because the national park had protected the survey area, timber harvesting, grazing, and hunting were not substantial factors. Analyses of Audubon Christmas Bird Count data across the US, including sites in numerous national parks, found that climate change shifted the average winter range of 254 bird species northward 30 ± 17 km (19 ± 11 mi) from 1975 to 2004 (La Sorte and Thompson 2007). The research found that the evening grosbeak (*Coccothraustes vespertinus*) disappeared from counts that included Rock Creek Park, Sleeping Bear Dunes National Lakeshore, and other parks.

Future risks

The first spatial analysis of projected climate trends across all the US national parks (Gonzalez et al. 2018) examined all 121 available climate model projections from the Intergovernmental Panel on Climate Change (IPCC 2013) for all four future emissions scenarios. Results indicated that continued CO_2 emissions under the highest emissions scenario (Representative Concentration Pathway [RCP] 8.5) could increase temperatures in the 21st century up to six times the increase

in the 20th century (Table 1). By 2100, annual average temperatures in national parks could increase up to 9°C (16°F), with the highest increases occurring in the national parks of Alaska, and rainfall could decline by as much as 28 percent, with the largest decreases occurring in the national parks of the US Virgin Islands (Figure 4).

Under continued CO_2 emissions, models project increased precipitation for much of the US (Figure 4). Across the mid-latitudes of the contiguous 48 states, from California to Florida, climate models do not agree, with some projecting precipitation increases and others projecting decreases. In higher latitudes, most models project increases. In lower latitudes, including in Everglades NP, most models project decreases. Even in regions where the average of climate model projections indicates a net increase in precipitation, warmer temperatures could increase aridity by increasing evapotranspiration (Byrne and O'Gorman 2015).

Published research on national park resources indicates that continued climate change could damage many natural and cultural resources (Gonzalez 2017). Projected risks include the following.

Glacier loss. Under the highest emissions scenario, climate change could completely melt the glaciers in Glacier NP by the 2040s (Hall and Fagre 2003; Brown et al. 2010).

Permafrost thaw. Thawing of permafrost in Bering Land Bridge National Preserve (Jones et al. 2011), Kobuk Valley NP (Necsoiu et al. 2013), and Noatak National Preserve (Balser et al. 2014) could continue with projected temperature increases under climate change.

Wildfire increase. Climate change under a high emissions scenario could increase wildfire frequencies by 2100 up to 1000% in Yellowstone NP and Grand Teton NP (Westerling et al. 2011b) and up to 300% in the Sierra Nevada of California, including in Yosemite NP (Westerling et al. 2011a). Climate change under a high emissions scenario could bring wildfire by 2100 to areas of northern Alaska where it is currently uncommon, including Gates of the Arctic NP and Preserve and Noatak National Preserve, and could double wildfire frequencies in central Alaska, including Denali NP and Preserve (Young et al. 2017, 2019). The observed upslope expansion of fire-adapted grasses in Hawai'i Volcanoes NP increases the risk of introduction of fire into a Hawaiian mountain ecosystem under climate change (Angelo and Daehler 2013).

Tree mortality. Increased aridity and reduced fog under continued climate change increase the risk of death of coast redwoods (*Sequoia sempervirens*), the tallest living beings on Earth, in Muir Woods National Monument (Johnstone and Dawson 2010; Fernández et al. 2015). Drought and bark beetle infestations under continued climate change increase risks of death of ponderosa pine in the Sierra Nevada, including Kings Canyon NP, Sequoia NP, and Yosemite NP (Goulden and Bales 2019), whitebark pine in Yellowstone NP (Chang et al. 2014), and piñon pine (*Pinus edulis*) in Bandelier National Monument (Williams et al. 2013).

Biome shifts. Under continued climate change, one-sixth of the national park area is highly vulnerable to poleward and upslope biome shifts, particularly shifts of boreal forest into tundra and deciduous broadleaf into temperate mixed and temperate conifer forest (Gonzalez et al. 2010). Habitat fragmentation due to urbanization, roads, and agriculture creates barriers to species dispersal that exacerbate the risk (Eigenbrod et al. 2015). Models project shifts of boreal forest into tundra in Bering Land Bridge National Preserve, Cape Krusenstern National Monument, Gates of the Arctic NP and Preserve, Kobuk Valley NP, and Noatak National Preserve (Rupp et al. 2000, 2001; Jorgenson et al. 2015). Boreal forest could shift into tundra and alpine ecosystems in Denali NP and Preserve (Stueve et al. 2011; Brodie et al. 2019).

Inundation from sea level rise. Sea level rise due to climate change could inundate up to half of Everglades NP by 2100 (Park et al. 2017) and parts of the Statue of Liberty National Monument (Marzeion and Levermann 2014), the Jefferson Memorial and other national parks in Washington, DC (Ayyub et al. 2012), New Bedford Whaling National Historical Park (Massachusetts Office of Coastal Zone Management 2017), Canaveral National Seashore (Foster et al. 2017), Assateague Island National Seashore (Murdukhayeva et al. 2013), and Golden Gate NRA (CMG 2016; Hoover et al. 2017). Sea level rise could inundate most suitable habitat for northern elephant seals (*Mirounga angustirostris*) in Point Reyes National Seashore by 2100 (Funayama et al. 2013). An analysis of 22 coastal national parks indicated that the parks along the Atlantic Ocean were most at risk from sea level rise (Pendleton et al. 2010). An analysis of projections for 118 coastal national parks indicated that Cape Hatteras National Seashore could experience the highest sea level rise among the parks (Caffrey et al. 2018).

Coral bleaching. Coral reefs in the National Park of American Samoa, Biscayne NP, and national parks in
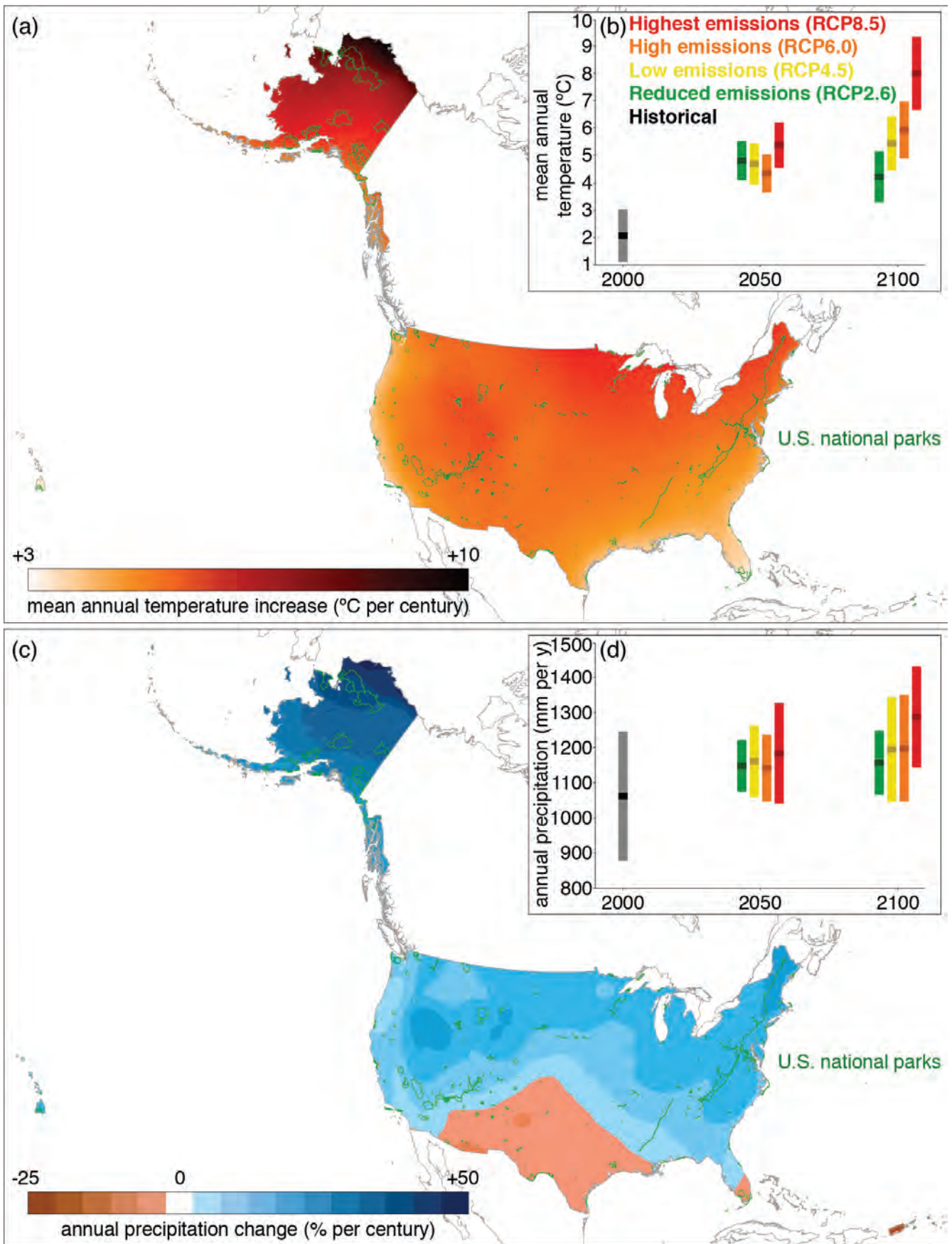
FIGURE 4. Climate change projections, 1971–2000 to 2071–2100 (Gonzalez et al. 2018). (a) Projected increase in mean annual temperature (ºC per century) for RCP8.5. (b) Mean annual temperature (ºC) of the national park area; dark band = mean, bars = standard deviations of annual values (historical) or climate model ensembles (projections). (c) Projected change in annual precipitation (% per century), relative to the 1971–2000 average, for RCP8.5. (d) Annual precipitation (mm per year).

the US Virgin Islands are at risk of bleaching and death under continued climate change (Eakin et al. 2010; IPCC 2019b; Thomas et al. 2019), although no research has yet quantified the potential mortality. Certain coral populations in the National Park of American Samoa show acclimatization and evolutionary adaptation to increased temperatures (Palumbi et al. 2014).

Ocean acidification. Corals and other marine life in Dry Tortugas NP (Kuffner et al. 2013) and Channel Islands NP and Cabrillo National Monument (Marshall et al. 2017) are at risk of dissolving in acidified waters under continued climate change. Kelp (*Macrocystis pyrifera*) in Channel Islands NP can decrease water acidity (+0.1 to +0.2 pH) through uptake of CO_2 in photosynthesis (Kapsenberg and Hofmann 2016; Hoshijima and Hofmann 2019), potentially reducing the magnitude of acidification in the kelp forests.

Plant species changes. Increased aridity under continued climate change could, under the highest emissions scenario, nearly eliminate suitable habitat for Joshua trees (*Yucca brevifolia*) from Joshua Tree NP by 2100 (Cole et al. 2011; Sweet et al. 2019). Saguaro cactus (*Carnegiea gigantea*) in Saguaro NP is sensitive to drought and wildfire under climate change (Springer et al 2015, Winkler et al. 2018). The Haleakalā silversword ('ahinahina; *Argyroxiphium sandwicense macrocephalum*), listed as threatened under the US Endangered Species Act (ESA), is vulnerable to extinction due to increasing aridity under climate change (Krushelnycky et al. 2013). Climate change could substantially reduce the extent of alpine meadows in Kings Canyon NP, Sequoia NP, and Yosemite NP (Maher et al. 2017). Climate change could cause tree species turnover in many eastern US national parks (Fisichelli et al. 2014; Zolkos et al. 2015). An advance of spring warmth in 276 national parks could cause earlier blooming of flowering plants (Monahan et al. 2016).

Mammal species declines. The polar bear (*Ursus maritimus*), found in Bering Land Bridge National Preserve, Cape Krusenstern National Monument, and across the Arctic, is listed as endangered under the ESA from reduction of sea ice habitat due to climate change (US Department of the Interior 2008). Climate change increases risks of extirpation of desert bighorn sheep (*Ovis canadensis nelsoni*), listed as endangered under the ESA, at low elevations, and genetic isolation at high elevations, in Death Valley NP, Joshua Tree NP, and Mojave National Preserve (Epps et al. 2006). Climate change could shift habitat for the pika (*Ochotona princeps*) upslope and nearly extirpate the species from Lassen Volcanic NP (Stewart et al. 2015). Big Bend NP,

Great Smoky Mountains NP, and five other parks may lose mammal species due to loss of habitat, with bat and rodent species most at risk (Burns et al. 2003). Climate change under a medium emissions scenario may reduce habitat for half of mammal and bird species in Bering Land Bridge National Preserve, Cape Krusenstern National Monument, Gates of the Arctic NP and Preserve, Kobuk Valley NP, and Noatak National Preserve by 2100 (Marcot et al. 2015).

Bird species changes. The rufa red knot (*Calidris canutus rufa*), a migratory shorebird found in Padre Island National Seashore and along the Atlantic coast, is listed as threatened under the ESA from sea level rise, reductions in food species due to climate change, and habitat loss due to urban development (US Department of the Interior 2014). Climate change could reduce greater sage-grouse (*Centrocercus urophasianus*) populations by half by 2045 in and around Craters of the Moon National Monument and Preserve from fire increases, cheatgrass invasion, and sagebrush loss (Boyte et al. 2016; Coates et al. 2016). Climate change increases risks of significant declines in native forest birds in Hawai'i, including Hawai'i Volcanoes NP, from avian malaria (Liao et al. 2015). Numerous national parks could lose local bird species and be colonized by migrants due to climate change, with an average 23% species turnover in 274 parks (Wu et al. 2018).

Reptile species declines. The green turtle (*Chelonia mydas*), listed as endangered under the ESA, is at risk of flooding of nests at Canaveral National Seashore from hurricanes (Pike and Stiner 2007), whose intensity climate change may increase (Ting et al. 2019). The desert tortoise (*Gopherus agassizii*), listed as threatened under the ESA, is at risk of dying in extreme heat or drought in Joshua Tree NP (Lovich et al. 2014). Modeling indicates that a temperature increase of 3ºC (5ºF) could reduce the area of suitable habitat for the tortoise in Joshua Tree NP by four-fifths (Barrows et al. 2014).

Amphibian species declines. The Shenandoah salamander (*Plethodon shenandoah*), listed as endangered under the ESA and found only in Shenandoah NP, is at risk of upslope shifts and contraction of its habitat due to rising temperatures and cloud base height under climate change (Grant et al. 2018). Climate change may reduce suitable stream habitat by up to half for northern dusky salamander (*Desmognathus fuscus*), northern two-lined salamander (*Eurycea bislineata*), and northern red salamander (*Pseudotriton ruber*) in Chesapeake and Ohio Canal National Historical Park, Prince William Forest Park, and Rock Creek Park (Grant et al. 2014).

Fish species declines. Climate change increases the risk of lethal water temperatures for salmon (*Oncorhynchus* spp.) spawning in Lake Clark NP (Mauger et al. 2017). Alewives (*Alosa pseudoharengus*) and blueback herring (*Alosa aestivalis*), which migrate annually from the Atlantic Ocean up into Rock Creek Park to spawn, are at risk of population declines of one-third and two-thirds, respectively, by 2100 with continued climate change under a medium emissions scenario (Lynch et al. 2015; Tommasi et al. 2015).

Butterfly species local loss. Increased temperatures could eliminate suitable habitat for the Karner blue butterfly (*Lycaeides melissa samuelis*) from Indiana Dunes National Park, where the species may have already been extirpated by hot temperatures in 2012 (Patterson et al. 2020). Hotter temperatures accelerate larval development, increase larval mortality, and shorten the lifetime of wild lupines (*Lupinus perennis*), their food source (Grundel and Pavlovic 2007; Patterson et al. 2020).

Invasive species increase. Continued climate change contributes to a high risk of invasive non-native species on one-eighth of the area of the national park system, due to hotter, moister conditions, disturbances, and carbon enrichment (Early et al. 2016). In Rocky Mountain NP, climate change under high emissions could quadruple the area suitable for cheatgrass (*Bromus tectorum*) by 2050 (West et al. 2015). The Appalachian National Scenic Trail is at high risk of increased spread of the invasive tree-of-heaven (*Ailanthus altissima*) (Clark et al. 2014).

Earlier cherry tree blooming. Monitoring of tree blooming in Washington, DC, and Baltimore, Maryland, location of many national parks, showed a statistically significant advance of cherry tree blooming by a week from 1970 to 1999 (Abu-Asab et al. 2001). Continued warming could advance peak bloom of cherry trees around the Tidal Basin, part of the National Capital Parks, by a week to a month by 2100 (Chung et al. 2011).

Archaeological artifact loss. Exposure of archaeological artifacts as glaciers melt in Wrangell-St. Elias NP and Preserve and Lake Clark NP and Preserve can cause organic objects to decompose and be lost forever (Dixon et al. 2005; VanderHoek et al. 2012).

Archaeological site erosion. Monitoring of 11 archaeological sites in Channel Islands NP from 2013 to 2017 showed that the sites are sensitive to erosion at sea cliffs and upland gullies caused by sea level rise and increased precipitation, two hazards exacerbated by climate change (Jazwa and Johnson 2018). Sites experienced erosion of 4% to 56% of their surface area and gully enlargement or cliff wall retreat up to 16 cm (6 in.) in a year. A separate analysis of coastal topography, land use, and tides in the park indicated a high vulnerability to erosion of archaeological resources at numerous sites (Reeder-Myers 2015).

Adaptation of resource management

Adaptation to climate change is the adjustment of practices to moderate future harm (IPCC 2014). Adaptation in US national parks cannot completely prevent alteration of park resources under climate change (Baron et al. 2009). Legal analysis indicates that the legislation that established the National Park Service, the Organic Act of 1916, gives the agency broad discretion to respond to climate change (Biber and Esposito 2016). The *Revisiting Leopold* report (National Park System Advisory Board 2012) recommended the management of national parks for potential future conditions rather than attempting to return them to past states.

Climate change adaptation measures for resource management implemented in the field in U.S. national parks and published in the scientific literature include conservation of refugia in Joshua Tree NP (Barrows and Murphy-Mariscal 2012; Sweet et al. 2019) and propagation of heat-resistant corals in Biscayne NP (Lirman et al. 2010; Schopmeyer et al. 2017). Aiming to maintain viable populations of its namesake tree, Joshua Tree NP protects climate change refugia (locations that potentially retain suitable conditions for a species) that have been identified by spatial analyses of climate projections and species sensitivity (Barrows and Murphy-Mariscal 2012; Sweet et al. 2019). The park prioritizes the refugia for invasive species control, fire suppression, and ecological monitoring. Biscayne NP is raising, in underwater nurseries, local corals resistant to warm waters and planting them to establish more heat-resistant reefs (Lirman et al. 2010; Schopmeyer et al. 2017).

Field adaptation measures under consideration in national parks include raising and planting heat-resistant local corals in the National Park of American Samoa (Morikawa and Palumbi 2019), conservation of climate refugia for alpine plants in Devils Postpile National Monument (Morelli et al. 2016), conservation of cool-water refugia for brook trout (*Salvelinus fontinalis*) in Shenandoah NP (Briggs et al. 2018), and prescribed burning in forests in Kings Canyon NP, Sequoia NP, and Yosemite NP to reduce future risks of high-severity fire and increase survival of older trees during droughts

(van Mantgem et al. 2016). In addition, Golden Gate NRA is developing sea level rise adaptation measures for Crissy Field in San Francisco, aimed at maintaining a natural shoreline and avoiding hard engineering structures (CMG 2016). Measures include augmenting a sand beach and expanding a coastal wetland to increase capacity to absorb water surges.

Climate change adaptation planning efforts include scenario planning in national parks in Alaska (Ernst and van Riemsdijk 2013; Knapp et al. 2017), Badlands NP (Miller et al. 2017), Wind Cave NP (Symstad et al. 2017), and other parks; structured decision-making in Shenandoah NP (Grant et al. 2013); social and ecological systems modeling in Badlands NP and Wind Cave NP (Beeton et al. 2019); and historic building management planning in Cape Lookout National Seashore (Xiao et al. 2019). Numerous national parks have integrated climate change considerations into official plans, including general management plans, foundation documents, and resource stewardship strategies.

Carbon solutions

Reducing CO_2 emissions from cars, power plants, deforestation, and other human sources directly targets the cause of climate change. Assessment of emissions reduction options by the IPCC (2018) has confirmed that it is still possible to limit the global temperature increase to 1.5°–2°C (3°–4°F), the goal of the Paris Agreement (UNFCCC 2015). Over the period 2000–2018, global energy efficiency increases and waste reduction saved 13% of the energy that the world would have otherwise used, equivalent to the combined fossil fuel energy use of Brazil, Canada, Germany, and India (IEA 2019). Global actions to replace coal, oil, and natural gas in electricity generation with solar, wind, hydroelectric, and other renewable sources doubled renewable energy capacity from 2009 to 2018, adding an electricity generating capacity equivalent to 1200 nuclear power plants (IRENA 2019).

The US cut greenhouse gas emissions 12% from 2007 to 2017 through, in part, energy conservation, improved efficiency, renewable energy, and public transit (USEPA 2019). The US Climate Alliance, which in 2020 includes 24 states and Puerto Rico, cut emissions 16% from 2005 to 2017, on track to meet the Paris Agreement goal (US Climate Alliance 2019).

US national parks have implemented emissions reduction actions. Yosemite NP reduced greenhouse gas emissions per visitor 10% from 2008 to 2011 through energy conservation, energy-efficient lighting, solar energy, recycling, water conservation, and public transportation (Villalba et al. 2013). Greenhouse gas emissions inventories of 18 national parks showed that visitor cars produced 75% of park emissions (Steuer 2010). Yosemite NP helped to set up a regular bus route from the nearest Amtrak rail station to Yosemite Valley (Figure 5) and shuttle buses within the park that

FIGURE 5. A Yosemite Area Regional Transportation System bus in Yosemite NP that helped the park reduce carbon emissions per visitor 10% from 2008 to 2011 (Villalba et al. 2013).

allow people, including this author, to visit car-free. Rocky Mountain NP set up a shuttle bus system in 1978, the first of many that reduce car use in national parks (Lawson et al. 2011). Golden Gate NRA reduced greenhouse gas emissions 25% from 2010 to 2015 (NPS 2016) through energy conservation, energy-efficient lighting, and a solar array on the roof of the Cell House on Alcatraz Island (Figure 6). In 2018, to offset its remaining emissions, the park began funding the capture of waste methane, a greenhouse gas 28 times more potent than CO_2 (IPCC 2013), at a dairy farm and landfill offsite (NPS 2019). Instead of being emitted into the air, methane is used to produce electricity. The amount of greenhouse gas emissions reduced through methane capture balances park emissions, making Golden Gate NRA carbon neutral. Other parks have developed emissions reductions plans as part of the National Park Service Climate Friendly Parks program.

Natural climate solutions include forest conservation and ecosystem restoration, since trees and other vegetation naturally reduce climate change by removing CO_2 from the atmosphere and storing it in biomass. Coast redwood forest near Redwood NP contains 2600 tons of carbon per hectare, more than any other ecosystem in the world (Van Pelt et al. 2016). The 27 national parks in California together contain as much carbon as the annual emissions of over 7 million Americans, or the combined population of the cities of Boston, Charlotte, Dallas, Kansas City, Los Angeles, and Miami (Gonzalez et al. 2015). This is a substantial amount of carbon, but those millions of people can burn the equivalent of all the carbon in the coast redwoods and other vegetation in the national parks in California in just one year. This shows that forest conservation is insufficient as a sole solution, pointing to the need to reduce greenhouse emissions from fossil fuel burning.

Reducing CO_2 emissions can avert the most extreme temperature increases in national parks in the future. The IPCC emissions reduction scenario (RCP2.6), in which the world would meet the Paris Agreement goal, would lower projected heating in national parks by two-thirds by 2100, compared with the highest emissions scenario (RCP8.5) (Gonzalez et al. 2018). The reduced heating could produce substantial benefits on the ground. While the highest emissions scenario puts 16% of plant and animal species globally at risk of extinction, the risk drops to 5% under the emissions reduction scenario (Urban 2015). Similarly, global sea level could rise 84 cm (33 in.) under the highest

FIGURE 6. Solar energy array on Alcatraz Island in Golden Gate NRA that helped the park reduce carbon emissions 25% from 2010 to 2015 (NPS 2016).

emissions scenario but rise 43 cm (17 in.) under the emissions reduction scenario (IPCC 2019b). In Yosemite NP, climate change under the highest emissions scenario could triple burned area by 2100, but a low emissions scenario could keep wildfires near to their current level (Westerling et al. 2011a).

The US national parks protect irreplaceable natural areas and cultural sites. Cutting carbon pollution would reduce human-caused climate change and help protect our national parks for future generations.

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