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

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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 ± 0.2ºC (1.8 ± 0.4ºF) 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 9ºC (16ºF) 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 0.9º ± 0.1ºC (1.6 ± 0.2ºF) 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 widespread physical and ecological impacts (Gonzalez 2017). Without reductions of emissions of carbon dioxide (CO₂), 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 ± 0.2ºC (1.8 ± 0.4ºF) 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, 4.3ºC (~8ºF) per century, 

| Area | Temperature | Precipitation | Temperature | Precipitation |
|------|-------------|---------------|-------------|---------------|
|      | 1895–2010   | 2000–2100     | RCP2.6      | RCP8.5        |
| km²  | ºC per century | % per century | ºC per century | % per century |
|      |             |               | RCP2.6      | RCP8.5        |
| 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 ± 4 * | 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 |

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 ± 0.1ºC per century**, 7 ± 2% per century***; national parks 48, 0.8 ± 0.1ºC 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.
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](image-url)
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
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. 2018). In Yosemite NP, climate change shifted sub-alpine 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 $0.7 \pm 0.1^\circ C$ ($1.3 \pm 0.2^\circ F$) 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 $0.8 \pm 0.2^\circ C$ ($1.4 \pm 0.4^\circ F$) 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 CO₂ concentrations from human activities are raising the acidity of ocean water as the CO₂ 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 CO₂ 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 $3^\circ C$ ($-5^\circ F$) (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 $30 \pm 17$ km ($19 \pm 11$ 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 CO₂ 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 9ºC (16ºF), 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 CO₂ 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 (Murdokhayeva 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 (Fuinayama 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 (°C per century) for RCP8.5. (b) Mean annual temperature (°C) 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 CO₂ 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 (Krushelnick 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 (Li 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 3°C (5°F) 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.
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 CO₂ 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).](image-url)
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 \( \text{CO}_2 \) (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 \( \text{CO}_2 \) 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 \( \text{CO}_2 \) 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 emissions scenario, compared to just 16 cm (6 in.) under the emissions reduction scenario.
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.

References
Abatzoglou, J.T., and A.P. Williams. 2016. Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences of the USA* 113: 11 770–11 775. https://doi.org/10.1073/pnas.1607171113

Abu-Asab, M.S., P. M. Peterson, S.G. Shetler, and S.S. Orli. 2001. Earlier plant flowering in spring as a response to global warming in the Washington, DC, area. *Biodiversity and Conservation* 10: 597–612. https://doi.org/10.1023/A:1016667125469

Angelo, C.L., and C.C. Daehler. 2013. Upward expansion of fire-adapted grasses along a warming tropical elevation gradient. *Ecography* 36: 551–559. https://doi.org/10.1111/j.1600-0587.2012.07754.x

Ayyub, B.M., H.G. Braileanu, and N. Qureshi. 2012. Prediction and impact of sea level rise on properties and infrastructure of Washington, DC. *Risk Analysis* 32: 1901–1918. https://doi.org/10.1111/j.1539-6924.2011.01710.x

Balser, A.W., J.B. Jones, and R. Gens. 2014. Timing of retrogressive thaw slump initiation in the Noatak Basin, northwest Alaska, USA. *Journal of Geophysical Research: Earth Surface* 119: 1106–1120. https://doi.org/10.1002/2013JF002889

Baron, J.S., L. Gunderson, C.D. Allen, E. Fleishman, D. McKenzie, L.A. Meyerson, J. Oropeza, and N. Stephenson. 2009. Options for national parks and reserves for adapting to climate change. *Environmental Management* 44: 1033–1042. https://doi.org/10.1007/s00267-009-9296-6

Barrows, C.W., J. Hoines, K.D. Fleming, M.S. Vamstad, M. Murphy-Mariscal, K. Lalumiere, and M. Harding. 2014. Designing a sustainable monitoring framework for assessing impacts of climate change at Joshua Tree National Park, USA. *Biodiversity and Conservation* 23: 3263–3285. https://doi.org/10.1007/s10531-014-0779-2

Barrows, C.W., and M.L. Murphy-Mariscal. 2012. Modeling impacts of climate change on Joshua trees at their southern boundary: How scale impacts predictions. *Biological Conservation* 152: 29–36. https://doi.org/10.1016/j.biocon.2012.03.028

Bednaršek, N., R.A. Feely, N. Tolimieri, A.J. Hermann, S.A. Siedlecki, G.G. Waldbusser, P. McElhany, S.R. Alin, T. Klinger, B. Moore-Maley, and H.O. Pörtner. 2017. Exposure history determines pteropod vulnerability to ocean acidification along the US West Coast. *Scientific Reports* 7: 4526. https://doi.org/10.1038/s41598-017-03934-z

Beeton, T.A., S.M. McNeeley, B.W. Miller, and D.S. Ojima. 2019. Grounding simulation models with qualitative case studies: Toward a holistic framework to make climate science usable for US public land management. *Climate Risk Management* 23: 50–66. https://doi.org/10.1016/j.crm.2018.09.002

Berner, L.T., B.E Law, A.J.H. Meddens, and J.A. Hicke. 2017. Tree mortality from fires, bark beetles, and timber harvest during a hot and dry decade in the western United States (2003–2012). *Environmental Research Letters* 12: 065005. https://doi.org/10.1088/1748-9326/aa6f94

Biber, E., and E.L. Esposito. 2016. The National Park Service Organic Act and climate change. *Natural Resources Journal* 56: 193–245. https://digitalrepository.unm.edu/cgi/viewcontent.cgi?article=1017&context=nrj

Boyte, S.P., B.K. Wylie, and D.J. Major. 2016. Cheatgrass percent cover change: Comparing recent estimates to climate change-driven predictions in the northern Great Basin. *Rangeland Ecology and Management* 69: 265–279. https://doi.org/10.1016/j.rama.2016.03.002

Briggs, M.A., J.W. Lane, C.D. Snyder, E.A. White, Z.C. Johnson, D.L. Nelms, and N.P. Hitt. 2018. Shallow bedrock limits groundwater seepage-based headwater climate refugia. *Limnologica* 68: 142–156. https://doi.org/10.1016/j.limno.2017.02.005
Chen, I.C., J.K. Hill, R. Ohlemüller, D.B. Roy, and C.D. Thomas. 2011. Rapid range shifts of species associated with high levels of climate warming. *Science* 333: 1024–1026.
https://doi.org/10.1126/science.1206432

Chung, U., L. Mack, J. Yun, and S.H. Kim. 2011. Predicting the timing of cherry blossoms in Washington, DC and Mid-Atlantic States in response to climate change. *PLoS One* 6: e27439.
https://doi.org/10.1371/journal.pone.0027439

Clark, J., Y. Wang, and P.V. August. 2014. Assessing current and projected suitable habitats for tree-of-heaven along the Appalachian Trail. *Philosophical Transactions of the Royal Society of London B* 369: 20130192.
https://doi.org/10.1098/rstb.2013.0192

CMG Landscape Architecture. 2016. *Crissy Field + Sea Level Rise-Up*. San Francisco: CMG Landscape Architecture.
https://issuu.com/parks-conservancy/docs/crissy_field_sea_level_rise_analysis

Coates, P.S., M.A. Ricca, B.G. Prochazka, M.L. Brooks, K.E. Doherty, T. Kroger, E.J. Blomberg, C.A. Hagen, and M.L. Casazza. 2016. Wildfire, climate, and invasive grass interactions negatively impact an indicator species by reshaping sagebrush ecosystems. *Proceedings of the National Academy of Sciences of the USA* 113: 12 745–12 750.
https://doi.org/10.1073/pnas.1606898113

Cole, K.L., K. Ironside, J. Eischeid, G. Garfin, P.B. Duffy, and C. Toney. 2011. Past and ongoing shifts in Joshua tree distribution support future modeled range contraction. *Ecological Applications* 21: 137–149.
https://doi.org/10.1890/09-1800.1

Diffenbaugh, N.S., D.L. Swain, and D. Touma. 2015. Anthropogenic warming has increased drought risk in California. *Proceedings of the National Academy of Sciences of the USA* 112: 3931–3936.
https://doi.org/10.1073/pnas.1422385112

Dixon, E.J., W.F. Manley, and C.M. Lee. 2005. Glacier artifacts the emerging archaeology of glaciers and ice patches: Examples from Alaska’s Wrangell-St. Elias National Park and Preserve. *American Antiquity* 70: 129–143.
https://doi.org/10.2307/40035272
Eakin, C.M., J.A. Morgan, S.F. Heron, T.B. Smith, G. Liu, et al. 2010. Caribbean corals in crisis: Record thermal stress, bleaching, and mortality in 2005. *PLoS One* 5: e13969. https://doi.org/10.1371/journal.pone.0013969

Early, R., B.A. Bradley, J.S. Dukes, J.J. Lawler, J.D. Olden, D.M. Blumenthal, P. Gonzalez, E.D. Grosholz, I. Ibañez, L.P. Miller, C.J.B. Sorte, and A.J. Tatem. 2016. Global threats from invasive alien species in the twenty-first century and national response capacities. *Nature Communications* 7: 12485. https://doi.org/10.1038/ncomms12485

Eigenbrod, F., P. Gonzalez, J. Dash, and I. Steyl. 2015. Vulnerability of ecosystems to climate change moderated by habitat intactness. *Global Change Biology* 21: 275–286. https://doi.org/10.1111/gcb.12669

Epps, C.W., P.J. Palsbøll, J.D. Wehausen, G.K. Roderick, and D.R. McCullough. 2006. Elevation and connectivity define genetic refugia for mountain sheep as climate warms. *Molecular Ecology* 15: 4295–4302. https://doi.org/10.1111/j.1365-294X.2006.03103.x

Ernst, K.M. and M. van Riemsdijk. 2013. Climate change scenario planning in Alaska’s National Parks: Stakeholder involvement in the decision-making process. *Applied Geography* 45: 22–28. https://doi.org/10.1016/j.apgeog.2013.08.004

Feely, R.A., S. Alin, B. Carter, N. Bednaršek, B. Hales, F. Chan, T.M. Hill, B. Gaylord, E. Sanford, R.H. Byrne, C.L. Sabine, D. Greeley, and L. Juranek. 2016. Chemical and biological impacts of ocean acidification along the west coast of North America. *Estuarine, Coastal, and Shelf Science* 183: 260–270. https://doi.org/10.1016/j.ecss.2016.08.043

Fernández, 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. https://doi.org/10.1111/gcb.13027

Fisichelli, N.A., S.R. Abella, M. Peters, and F.J. Krist. 2014. Climate, trees, pests, and weeds: Change, uncertainty, and biotic stressors in eastern US national park forests. *Forest Ecology and Management* 327: 31–39. https://doi.org/10.1016/j.foreco.2014.04.033

Foster, T.E., E.D. Stolen, C.R. Hall, R. Schaub, B.W. Duncan, D.K. Hunt, and J.H. Drese. 2017. Modeling vegetation community responses to sea-level rise on barrier island systems: A case study on the Cape Canaveral barrier island complex, Florida, USA. *PLoS One* 12: e0182605. https://doi.org/10.1371/journal.pone.0182605

Fountain, A., M. Hoffman, F. Granshaw, and J. Riedel. 2009. The ‘benchmark glacier’ concept—does it work? Lessons from the North Cascade Range, USA. *Annals of Glaciology* 50: 163–168. https://doi.org/10.3189/172756409787769690

Funayama, K., E. Hines, J. Davis, and S. Allen. 2013. Effects of sea-level rise on northern elephant seal breeding habitat at Point Reyes Peninsula, California. *Aquatic Conservation: Marine and Freshwater Ecosystems* 23: 233–245. https://doi.org/10.1002/aqc.2318

Gonzalez, P. 2017. Climate change trends, impacts, and vulnerabilities in US national parks. In Beissinger, S.R., D.D. Ackerly, H. Doremus, and G.E. Machlis, eds. *Science, Conservation, and National Parks*. Chicago: University of Chicago Press. https://doi.org/10.7208/chicago/9780226423142.003.0006

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. https://doi.org/10.1016/j.foreco.2015.03.040

Gonzalez, P., R.P. Neilson, J.M. Lenihan, and R.J. Drapek. 2010. Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change. *Global Ecology and Biogeography* 19: 755–768. https://doi.org/10.1111/j.1466-8238.2009.00558.x

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. https://doi.org/10.1088/1748-9326/aade09

Goulden, M.L., and R.C. Bales. 2019. California forest die-off linked to multi-year deep soil drying in 2012–2015 drought. *Nature Geoscience* 12: 632–637. https://doi.org/10.1038/s41561-019-0388-5
Grant, E.H.C., A.B. Brand, S.F.J. De Wekker, T.R. Lee, and J.E.B. Wofford. 2018. Evidence that climate sets the lower elevation range limit in a high-elevation endemic salamander. *Ecology and Evolution* 8: 7553–7562. https://doi.org/10.1002/ece3.4198

Grant, E.H.C., A.N.M. Wiewel, and K.C. Rice. 2014. Stream-water temperature limits occupancy of salamanders in Mid-Atlantic protected areas. *Journal of Herpetology* 48: 45–50. https://doi.org/10.1670/12-138

Grant, E.H.C., E.F. Zipkin, J.D. Nichols, and J.P. Campbell. 2013. A strategy for monitoring and managing declines in an amphibian community. *Conservation Biology* 27: 1245–1253. https://doi.org/10.1111/cobi.12137

Gruber, N., C. Hauri, Z. Lachkar, D. Loher, T.L. Frolicher, and G.K. Plattner. 2012. Rapid progression of ocean acidification in the California Current System. *Science* 337: 220–223. https://doi.org/10.1126/science.1216773

Grundel, R., and N.B. Pavlovic. 2007. Resource availability, matrix quality, microclimate, and spatial pattern as predictors of patch use by the Karner blue butterfly. *Biological Conservation* 135: 135–144. https://doi.org/10.1016/j.biocon.2006.10.003

Hall, M.H.P., and D.B. Fagre. 2003. Modeled climate-induced glacier change in Glacier National Park, 1850–2100. *BioScience* 53: 131–140. https://doi.org/10.1641/0006-3568(2003)053[0131:M-CIGCI]2.0.CO;2

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: E8349–E8357. https://doi.org/10.1073/pnas.1802316115

Huang, B., P.W. Thorne, V.F. Banzon, T. Boyer, G. Chepurin, J.H. Lawrimore, M.J. Menne, T.M. Smith, R.S. Vose, and H. Zhang. 2017. Extended reconstructed sea surface temperature, Version 5 (ERSSTv5): Upgrades, validations, and intercomparisons. *Journal of Climate* 30: 8179–8205. https://doi.org/10.1175/JCLI-D-16-0836.1

Hughes, T.P., K.D. Anderson, S.R. Connolly, S.F. Heron, J.T. Kerry, J.M. Lough, A.H. Baird, J.K. Baum, M.L. Berumen, T.C. Bridge, D.C. Claar, C.M. Eakin, J.P. Gilmour, N.A.J. Graham, H. Harrison, A.S. Hoey, M. Hoogenboom, R.J. Lowe, M.T. Mcculloch, J.M. Pandolfi, M. Pratchett, V. Schoepf, G. Torda, and S.K. Wilson. 2018. Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science* 359: 80–83. https://doi.org/10.1126/science.aan8048

IEA [International Energy Agency]. 2019. *Energy Efficiency 2019*. Paris: IEA. https://webstore.iea.org/download/direct/2891

Iknayan, K.J., and S.R. Beissinger. 2018. Collapse of a desert bird community over the past century driven by climate change. *Proceedings of the National Academy of Sciences of the USA* 115: 8597–8602. https://doi.org/10.1073/pnas.1805123115

IPCC [Intergovernmental Panel on Climate Change]. 2013. *Climate Change 2013: The Physical Science Basis*. T.F. Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, eds. Cambridge, UK, and New York: Cambridge University Press. https://www.ipcc.ch/report/ar5/wg1

IPCC [Intergovernmental Panel on Climate Change]. 2014. *Climate Change 2014: Impacts, Adaptation, and Vulnerability*. C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White, eds. Cambridge, UK, and New York: Cambridge University Press. https://www.ipcc.ch/report/ar5/wg2
IPCC [Intergovernmental Panel on Climate Change]. 2018. Global Warming of 1.5°C. V. Masson-Delmotte, 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. Geneva: IPCC. https://www.ipcc.ch/sr15

IPCC [Intergovernmental Panel on Climate Change]. 2019a. Climate Change and Land. P.R. Shukla, P.R., J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, and J. Malley, eds. Geneva: IPCC. https://www.ipcc.ch/srccl

IPCC [Intergovernmental Panel on Climate Change]. 2019b. The Ocean and Cryosphere in a Changing Climate. H.O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer, eds. Geneva: IPCC. https://www.ipcc.ch/srocc

IRENA [International Renewable Energy Agency]. 2019. Renewable Energy Statistics 2019. Abu Dhabi, UAE: IRENA. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Jul/IRENA_Renewable_energy_statistics_2019.pdf

Jacox, M.G., M.A. Alexander, N.J. Mantua, J.D. Scott, G. Hervieux, R.S. Webb, and F.E. Werner. 2018. Forcing of multiyear extreme ocean temperatures that impacted California current living marine resources in 2016. Bulletin of the American Meteorological Society 99: S27–S33. https://doi.org/10.1175/BAMS-D-17-0119.1

Jazwa, C.S. and K.N. Johnson. 2018. Erosion of coastal archaeological sites on Santa Rosa Island, California. Western North American Naturalist 78: 302–327. https://doi.org/10.3398/064.078.0307

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: 4533–4538. https://doi.org/10.1073/pnas.0915062107

Jones, B.M., G. Grosse, C.D. Arp, M.C. Jones, K.M. Walter Anthony, and V.E. Romanovsky. 2011. Modern thermokarst lake dynamics in the continuous permafrost zone, northern Seward Peninsula, Alaska. Journal of Geophysical Research 116: G00M03. https://doi.org/10.1029/2011JG001666

Jorgenson, M.T., B.G. Marcot, D.K. Swanson, J.C. Jorgenson, and A.R. DeGange. 2015. Projected changes in diverse ecosystems from climate warming and biophysical drivers in northwest Alaska. Climatic Change 130: 131–144. https://doi.org/10.1007/s10584-015-1681-5

Kennedy, J.J., N.A. Rayner, C.P. Atkinson, and R.E. Kille. 2019. An ensemble data set of sea surface temperature change from 1850: The Met Office Hadley Centre HadSST.4.0.0.0 data set. Journal of Geophysical Research: Atmospheres 124: 7719–7763. https://doi.org/10.1029/2018JD029867

Krushelnycky, P.D., L.L. Loope, T.W. Giambelluca, F. Starr, K. Starr, D.R. Drake, A.D. Taylor, and R.H. Robichaux. 2013. Climate-associated population declines reverse recovery and threaten future of an iconic high-elevation plant. Global Change Biology 19: 911–922. https://doi.org/10.1111/gcb.12111

Kuffner, I.B., T.D. Hickey, and J.M. Morrison. 2013. Calcification rates of the massive coral Siderastrea siderea and crustose coralline algae along the Florida Keys (USA) outer-reef tract. Coral Reefs 32: 987–997. https://doi.org/10.1007/s00338-013-1047-8

La Sorte, F.A., and F.R. Thompson. 2007. Poleward shifts in winter ranges of North American birds. Ecology 88: 1803–1812. https://doi.org/10.1890/06-1072.1

Larsen, C.F., R.J. Motyka, A.A. Arendt, K.A. Echemeyer, and P.E. Geissler. 2007. Glacier changes in southeast Alaska and northwest British Columbia and contribution to sea level rise. Journal of Geophysical Research 112: F01007. https://doi.org/10.1029/2006JF000586

Larsen, C.F., R.J. Motyka, A.A. Arendt, K.A. Echemeyer, and P.E. Geissler. 2007. Glacier changes in southeast Alaska and northwest British Columbia and contribution to sea level rise. Journal of Geophysical Research 112: F01007. https://doi.org/10.1029/2006JF000586

IRENA [International Renewable Energy Agency]. 2019. Renewable Energy Statistics 2019. Abu Dhabi, UAE: IRENA. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Jul/IRENA_Renewable_energy_statistics_2019.pdf

Jacox, M.G., M.A. Alexander, N.J. Mantua, J.D. Scott, G. Hervieux, R.S. Webb, and F.E. Werner. 2018. Forcing of multiyear extreme ocean temperatures that impacted California current living marine resources in 2016. Bulletin of the American Meteorological Society 99: S27–S33. https://doi.org/10.1175/BAMS-D-17-0119.1

Jazwa, C.S. and K.N. Johnson. 2018. Erosion of coastal archaeological sites on Santa Rosa Island, California. Western North American Naturalist 78: 302–327. https://doi.org/10.3398/064.078.0307

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: 4533–4538. https://doi.org/10.1073/pnas.0915062107

Jones, B.M., G. Grosse, C.D. Arp, M.C. Jones, K.M. Walter Anthony, and V.E. Romanovsky. 2011. Modern thermokarst lake dynamics in the continuous permafrost zone, northern Seward Peninsula, Alaska. Journal of Geophysical Research 116: G00M03. https://doi.org/10.1029/2011JG001666

Jorgenson, M.T., B.G. Marcot, D.K. Swanson, J.C. Jorgenson, and A.R. DeGange. 2015. Projected changes in diverse ecosystems from climate warming and biophysical drivers in northwest Alaska. Climatic Change 130: 131–144. https://doi.org/10.1007/s10584-015-1681-5

Kennedy, J.J., N.A. Rayner, C.P. Atkinson, and R.E. Killick. 2019. An ensemble data set of sea surface temperature change from 1850: The Met Office Hadley Centre HadSST.4.0.0.0 data set. Journal of Geophysical Research: Atmospheres 124: 7719–7763. https://doi.org/10.1029/2018JD029867

Krushelnycky, P.D., L.L. Loope, T.W. Giambelluca, F. Starr, K. Starr, D.R. Drake, A.D. Taylor, and R.H. Robichaux. 2013. Climate-associated population declines reverse recovery and threaten future of an iconic high-elevation plant. Global Change Biology 19: 911–922. https://doi.org/10.1111/gcb.12111

Kuffner, I.B., T.D. Hickey, and J.M. Morrison. 2013. Calcification rates of the massive coral Siderastrea siderea and crustose coralline algae along the Florida Keys (USA) outer-reef tract. Coral Reefs 32: 987–997. https://doi.org/10.1007/s00338-013-1047-8

La Sorte, F.A., and F.R. Thompson. 2007. Poleward shifts in winter ranges of North American birds. Ecology 88: 1803–1812. https://doi.org/10.1890/06-1072.1

Larsen, C.F., R.J. Motyka, A.A. Arendt, K.A. Echelmeyer, and P.E. Geissler. 2007. Glacier changes in southeast Alaska and northwest British Columbia and contribution to sea level rise. Journal of Geophysical Research 112: F01007. https://doi.org/10.1029/2006JF000586

Lawson, S., R. Chamberlin, J. Choi, B. Swanson, B. Kiser, P. Newman, C. Monz, D. Pettebone, and L. Gamble. 2011. Modeling the effects of shuttle service on transportation system performance and quality of visitor experience in Rocky Mountain National Park. Transportation Research Record 2244: 97–106. https://doi.org/10.3141/2244-13
Liao, W., O. Elison Timm, C. Zhang, C.T. Atkinson, D.A. LaPointe, and M.D. Samuel. 2015 Will a warmer and wetter future cause extinction of native Hawaiian forest birds? Global Change Biology 21: 4342–4352. 
https://doi.org/10.1111/gcb.13005

Lirman, D., T. Thyberg, J. Herlan, C. Hill, C. Young-Lahiff, S. Schopmeyer, B. Huntington, R. Santos, and C. Drury. 2010. Propagation of the threatened staghorn coral Acropora cervicornis: Methods to minimize the impacts of fragment collection and maximize production. Coral Reefs 29: 729–735. 
https://doi.org/10.1007/s00338-010-0621-6

Lovich, J.E., C.B. Yackulic, J. Freilich, M. Agha, M. Austin, K.P. Meyer, T.R. Arundel, J. Hansen, M.S. Vamstad, and S.A. Root. 2014. Climatic variation and tortoise survival: Has a desert species met its match? Biological Conservation 169: 214–224. 
https://doi.org/10.1016/j.biocon.2013.09.027

Lubetkin, K.C., A.L. Westerling, and L.M. Kueppers. 2017. Climate and landscape drive the pace and pattern of conifer encroachment into subalpine meadows. Ecological Applications 27:1876–1887. 
https://doi.org/10.1002/eap.1574

Lynch, P.D., J.A. Nye, J.A. Hare, C.A. Stock, M.A. Alexander, J.D. Scott, K.L. Curti, and K. Drew. 2015. Projected ocean warming creates a conservation challenge for river herring populations. ICES Journal of Marine Science 72: 374–387. 
https://doi.org/10.1093/icesjms/fsu134

Macfarlane, W.W., J.A. Logan, and W.R. Kern. 2013. An innovative aerial assessment of Greater Yellowstone Ecosystem mountain pine beetle-caused whitebark pine mortality. Ecological Applications 23: 421–437. 
https://doi.org/10.1890/11-1982.1

Maher, S.P., T.L. Morelli, M. Hershey, A.L. Flint, I.E. Flint, C. Moritz, and S.R. Beissinger. 2017. Erosion of refugia in the Sierra Nevada meadows network with climate change. Ecosphere 8: e01673. 
https://doi.org/10.1002/ecs2.1673

Mansuy, N., C. Miller, M.A. Parisien, S.A. Parks, E. Batlloiri, and M.A. Moritz. 2019. Contrasting human influences and macro-environmental factors on fire activity inside and outside protected areas of North America. Environmental Research Letters 14: 064007. 
https://doi.org/10.1088/1748-9326/ab1bc5

Marcot, B.G., M.T. Jorgenson, J.P. Lawler, C.M. Handel, and A.R. DeGange. 2015. Projected changes in wildlife habitats in Arctic natural areas of northwest Alaska. Climatic Change 130: 145–154. 
https://doi.org/10.1007/s10584-015-1354-x

Marshall, K.N., I.C. Kaplan, E.E. Hodgson, A. Hermann, D.S. Busch, P. McElhany, T.E. Essington, C.J. Harvey, and E.A. Fulton. 2017. Risks of ocean acidification in the California Current food web and fisheries: ecosystem model projections. Global Change Biology 23: 1525–1539. 
https://doi.org/10.1111/gcb.13594

Massachusetts Office of Coastal Zone Management. 2017. Technical Report for the Massachusetts Sea Level Rise and Coastal Flooding Viewer. Boston: Massachusetts Office of Coastal Zone Management. 
https://www.mass.gov/files/documents/2016/10/qs/flood-viewer-tech-report.pdf

Mauger, S., R. Shaftel, J.C. Leppi, and D.J. Rinella. 2017. Summer temperature regimes in southcentral Alaska streams: Watershed drivers of variation and potential implications for Pacific salmon. Canadian Journal of Fisheries and Aquatic Sciences 74: 702–715. 
https://doi.org/10.1139/cjfas-2016-0076

McDowell, N.G., A.P. Williams, C. Xu, W.T. Pockman, L.T. Dickman, S. Sevanto, R. Pangle, J. Limousin, J. Plaut, D.S. Mackay, J. Ogee, C.D. Allen, R.A. Fisher, X. Jiang, J.D. Muss, D.D. Breshears, S.A. Rauscher, and C. Koven. 2016. Multi-scale predictions of massive conifer mortality due to chronic temperature rise. Nature Climate Change 6: 295–300. 
https://doi.org/10.1038/nclimate2873

Millar, C.I., R.D. Westfall, D.L. Delany, J.C. King, and L.J. Graumlich. 2004. Response of subalpine conifers in the Sierra Nevada, California, USA, to 20th-century warming and decadal climate variability. Arctic, Antarctic, and Alpine Research 36: 181–200. 
https://doi.org/10.1657/1523-0430(2004)036[0181:RO-SCIT]2.0.CO;2
Miller, B.W., A.J. Symstad, L. Frid, N.A. Fisichelli, and G.W. Schuurman. 2017. Co-producing simulation models to inform resource management: A case study from southwest South Dakota. *Ecosphere* 8: e02020. https://doi.org/10.1002/ecs2.2020

Monahan, W.B., A. Rosemartin, K.L. Gerst, N.A. Fisichelli, T. Ault, M.D. Schwartz, J.E. Gross, and J.F. Weltzin. 2016. Climate change is advancing spring onset across the US national park system. *Ecosphere* 7: e01465. https://doi.org/10.1002/ecs2.1465

Morelli, T.L., C. Daly, S.Z. Dobrowski, D.M. Dulen, J.L. Ebersole, S.T. Jackson, J.D. Lundquist, C.I. Millar, S.P. Maher, W.B. Monahan, K.R. Nydick, K.T. Redmond, S.C. Sawyer, S. Stock, and S.R. Beissinger. 2016. Managing climate change refugia for climate adaptation. *PLoS One* 11: e0159909. https://doi.org/10.1371/journal.pone.0159909

Morikawa, M.K. and S.R. Palumbi. 2019. Using naturally occurring climate resilient corals to construct bleaching-resistant nurseries. *Proceedings of the National Academy of Sciences of the USA* 116: 10 586–10 591. https://doi.org/10.1073/pnas.1721415116

Moritz, C., J.L. Patton, C.J. Conroy, J.L. Parra, G.C. White, and S.R. Beissinger. 2008. Impact of a century of climate change on small-mammal communities in Yosemite National Park, USA. *Science* 322: 261–264. https://doi.org/10.1126/science.1163428

Murdukhayeva, A., P. August, M. Bradley, C. LaBash, and N. Shaw. 2013. Assessment of inundation risk from sea level rise and storm surge in northeastern coastal national parks. *Journal of Coastal Research* 29: 1-16. https://doi.org/10.2112/JCOASTRES-D-12-00196.1

National Park System Advisory Board. 2012. *Revisiting Leopold: Resource Stewardship in the National Parks*. Washington, DC: National Park System Advisory Board. https://www.nps.gov/calltoaction/PDF/LeopoldReport_2012.pdf

Necsoiu, M., C.I Dinwiddie, G.R Walter, A. Larsen, and S.A Stothoff. 2013. Multi-temporal image analysis of historical aerial photographs and recent satellite imagery reveals evolution of water body surface area and polygonal terrain morphology in Kobuk Valley National Park, Alaska. *Environmental Research Letters* 8: 025007. https://doi.org/10.1088/1748-9326/8/2/025007

NOAA [National Oceanic and Atmospheric Administration]. 2019a. Relative sea level trend 9414290 San Francisco, California. https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9414290

NOAA [National Oceanic and Atmospheric Administration]. 2019b. Relative sea level trend 8518750 The Battery, New York. https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8518750

NOAA [National Oceanic and Atmospheric Administration]. 2019c. Relative sea level trend 8594900 Washington, District of Columbia. https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=8594900

NPS [National Park Service]. 2016. *Golden Gate National Recreation Area Climate Change Action Plan*. San Francisco: NPS. https://www.nps.gov/goga/learn/nature/upload/2016-Climate-Change-Action-Plan-1.pdf

NPS [National Park Service]. 2019. Becoming a carbon neutral park. https://www.nps.gov/goga/learn/nature/carbon-neutral-park.htm

Palumbi, S.R., D.J. Barshis, N. Traylor-Knowles, and R.A. Bay. 2014. Mechanisms of reef coral resistance to future climate change. *Science* 344: 895–898. https://doi.org/10.1126/science.1251336

Park, J., E. Stabenau, J. Redwine, and K. Kotun. 2017. South Florida’s encroachment of the sea and environmental transformation over the 21st century. *Journal of Marine Science and Engineering* 5: 31. https://doi.org/10.3390/jmse5030031

Patterson, T.A., R. Grundel, J.D.K. Dzurisin, R.L. Knuston, and J.J. Hellmann. 2020. Evidence of an extreme weather-induced phenological mismatch and a local extirpation of the endangered Karner blue butterfly. *Conservation Science and Practice* 2: e147. https://doi.org/10.1111/csp2.147

Pederson, G.T., D.B. Fagre, S.T. Gray, and L.J. Graumlich. 2004. Decadal-scale climate drivers for glacial dynamics in Glacier National Park, Montana, USA. *Geophysical Research Letters* 31: L12203. https://doi.org/10.1029/2004GL019770
Pederson, G.T., S.T. Gray, C.A. Woodhouse, J.L. Betancourt, D.B. Fagre, J.S. Littell, E. Watson, B.H. Luckman, and L.J. Graumlich. 2011. The unusual nature of recent snowpack declines in the North American Cordillera. *Science* 333: 332–335. https://doi.org/10.1126/science.1201570

Pelto, M.S. 2006. The current disequilibrium of North Cascade glaciers. *Hydrological Processes* 20: 769–779. https://doi.org/10.1002/hyp.6132

Pendleton, E.A., E.R. Thieler, and S.J. Williams. 2010. Importance of coastal change variables in determining vulnerability to sea- and lake-level change. *Journal of Coastal Research* 26: 176–183. https://doi.org/10.2112/08-1102.1

Pierce, D.W., T.P., Barnett, H.G. Hidalgo. T. Das, C. Bonfils, B.D. Santer, G. Bala, M.D. Dettinger, D.R. Cayan, A. Mirin, A.W. Wood, and T. Nozawa. 2008. Attribution of declining western US snowpack to human effects. *Journal of Climate* 21: 6425–6444. https://doi.org/10.1175/2008JCLI2405.1

Pike, D.A., and J.C. Stiner. 2007. Sea turtle species vary in their susceptibility to tropical cyclones. *Oecologia* 153: 471–478. https://doi.org/10.1007/s00442-007-0732-0

Raffa, K.F., B.H. Aukema, B.J. Bentz, A.L. Carroll, J.A. Hicke, M.G. Turner, and W.H. Romme. 2008. Cross-scale drivers of natural disturbances prone to anthropogenic amplification: The dynamics of bark beetle eruptions. BioScience 58: 501–517. https://doi.org/10.1641/B580607

Raffa, K.F., E.N. Powell, and P.A. Townsend. 2013. Temperature-driven range expansion of an irruptive insect heightened by weakly coevolved plant defenses. *Proceedings of the National Academy of Sciences of the USA* 110: 2193–2198. https://doi.org/10.1073/pnas.1216666110

Rayner, N.A., P. Brohan, D.E. Parker, C.K. Folland, J.J. Kennedy, M. Vainike, T.J. Ansell, and S.F.B. Tett. 2006. Improved analyses of changes and uncertainties in sea surface temperature measured in situ since the mid-nineteenth century: The HadSST2 dataset. *Journal of Climate* 19: 446–469. https://doi.org/10.1175/JCLI3637.1

Reeder-Myers, L.A. 2015. Cultural heritage at risk in the twenty-first century: A vulnerability assessment of coastal archaeological sites in the United States. *Journal of Island and Coastal Archaeology* 10: 436–445. https://doi.org/10.1080/15564894.2015.1008074

Riddell, E.A., K.J. Iknayan, B.O. Wolf, B. Sinervo, and S.R. Beissinger. 2019. Cooling requirements fueled the collapse of a desert bird community from climate change. *Proceedings of the National Academy of Sciences* 116: 21 609–21 615. https://doi.org/10.1073/pnas.1908791116

Rupp, T.S., F.S. Chapin, and A.M. Starfield. 2000. Response of subarctic vegetation to transient climatic change on the Seward Peninsula in north-west Alaska. *Global Change Biology* 6: 541–555. https://doi.org/10.1046/j.1365-2486.2000.00337.x

Rupp, T.S., F.S. Chapin, and A.M. Starfield. 2001. Modeling the influence of topographic barriers on treeline advance at the forest-tundra ecotone in northwestern Alaska. *Climatic Change* 48: 399–416. https://doi.org/10.1023/A:1010738502596

Rupp, D.E., P.W. Mote, N.L. Bindoff, P.A. Stott, and D.A. Robinson. 2013. Detection and attribution of observed changes in Northern Hemisphere spring snow cover. *Journal of Climate* 26: 6904–6914. https://doi.org/10.1175/JCLI-D-12-00563.1

Schopmeyer, S.A., D. Lirman, E. Bartels, D.S. Gilliam, E.A. Goergen, S.P. Griffin, M.E. Johnson, C. Lustic, K. Maxwell, and C.S. Walter. 2017. Regional restoration benchmarks for *Acropora cervicornis*. *Coral Reefs* 36: 1047–1057. https://doi.org/10.1007/s00338-017-1596-3

Slangen, A.B.A, J.A. Church, C. Agosta, X. Fettweis, B. Marzeion, and K. Richter. 2016. Anthropogenic forcing dominates global mean sea-level rise since 1970. *Nature Climate Change* 6: 701–705. https://doi.org/10.1038/nclimate2991

Springer, A.C., D.E. Swann, and M.A. Crimmins. 2015. Climate change impacts on high elevation saguaro range expansion. *Journal of Arid Environments* 116: 57–62. https://doi.org/10.1016/j.jaridenv.2015.02.004
Stephenson, N.L., A.J. Das, N.J. Amperey, B.M. Bulaon, and J.L. Yee. 2019. Which trees die during drought? The key role of insect host-tree selection. *Journal of Ecology* 107: 2383–2401. https://doi.org/10.1111/1365-2745.13176

Steuer, C. 2010. Climate friendly parks: Performing greenhouse gas inventories at US national parks and implications for public sector greenhouse gas protocols. *Applied Geography* 30: 475–482. https://doi.org/10.1016/j.apgeog.2010.03.005

Stewart, J.A.E., J.D. Perrine, L.B. Nichols, J.H. Thorne, C.I. Millar, K.E. Goehring, C.P. Massing, and D.H. Wright. 2015. Revisiting the past to foretell the future: Summer temperature and habitat area predict pika extirpations in California. *Journal of Biogeography* 42: 880–890. https://doi.org/10.1111/jbi.12466

Stueve, K.M., R.E. Isaacs, L.E. Tyrrell, and R.V. Demore. 2011. Spatial variability of biotic and abiotic tree establishment constraints across a treeline ecotone in the Alaska Range. *Ecology* 92: 496–506. https://doi.org/10.1890/09-1725.1

Suarez, F., D. Binkley, M.W. Kaye, and R. Stottlemeyer. 1999. Expansion of forest stands into tundra in the Noatak National Preserve, northwest Alaska. *Ecocience* 6: 465–470. https://doi.org/10.1080/11956860.1999.11682538

Sweet, L.C., T. Green, J.G.C. Heintz, N. Frakes, N. Grauer, J.S. Rangitsch, J.E. Rodgers, S. Heacox, and C.W. Barrows. 2019. Congruence between future distribution models and empirical data for an iconic species at Joshua Tree National Park. *Ecosphere* 10: e02763. https://doi.org/10.1002/ecs2.2763

Symstad, A.J., N.A. Fischelli, B.W. Miller, E. Rowland, and G.W. Schuurman. 2017. Multiple methods for multiple futures: Integrating qualitative scenario planning and quantitative simulation modeling for natural resource decision making. *Climate Risk Management* 17: 78–91. https://doi.org/10.1016/j.crm.2017.07.002

Tedesche, M.E., E.D. Trochim, S.R. Fassnacht, and G.J. Wolken. 2019. Extent changes in the perennial snowfields of Gates of the Arctic National Park and Preserve, Alaska. *Hydrology* 6: 53. https://doi.org/10.3390/hydrology6020053

Thomas, L., E.H. López, M.K. Morikawa, and S.R. Palumbi. 2019. Transcriptomic resilience, symbiont shuffling, and vulnerability to recurrent bleaching in reef-building corals. *Molecular Ecology* 28: 3371–3382. https://doi.org/10.1111/mec.15143

Ting, M., J.P. Kossin, S.J. Camargo, and C. Li. 2019. Past and future hurricane intensity change along the US East Coast. *Scientific Reports* 9: 7795. https://doi.org/10.1038/s41598-019-44252-w

Tommasi, D., J. Nye, C. Stock, J.A. Hare, M. Alexander, and K. Drew. 2015. Effect of environmental conditions on juvenile recruitment of alewife (*Alosa pseudoharengus*) and blueback herring (*Alosa aestivalis*) in fresh water: A coastwide perspective. *Canadian Journal of Fisheries and Aquatic Sciences* 72: 1037–1047. https://doi.org/10.1139/cjfas-2014-0259

Udall, B. and J. Overpeck. 2017. The twenty-first century Colorado River hot drought and implications for the future. *Water Resources Research* 53: 2404–2418. https://doi.org/10.1002/2016WR019638

UNFCCC [United Nations Framework Convention on Climate Change]. 2015. Adoption of the Paris Agreement. Document FCCC/CP/2015/10/Add1, Decision 1/CP21. Bonn: UNFCCC. https://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf#page=2

United States Climate Alliance. 2019. *Annual Report*. Washington, DC: US Climate Alliance. http://www.usclimatealliance.org/s/USCA_2019-Annual-Report_final.pdf

United States Department of the Interior. 2008. Endangered and threatened wildlife and plants; Determination of threatened status for the polar bear (*Ursus maritimus*) throughout its range. *Federal Register* 73 (95): 28312–28303. https://www.govinfo.gov/content/pkg/FR-2008-05-15/pdf/E8-11105.pdf

United States Department of the Interior. 2014. Endangered and threatened wildlife and plants; Threatened species status for the rufa red knot. *Federal Register* 79 (238): 73706–73748. https://www.govinfo.gov/content/pkg/FR-2014-12-11/pdf/2014-28338.pdf

Urban, M.C. 2015. Accelerating extinction risk from climate change. *Science* 348: 571–573. https://doi.org/10.1126/science.aaa4984
van Mantgem, P.J., C.D. Allen, A.K. Macalady, D. Griffin, C.A. Woodhouse, D.M. Meko, T.W. Swetnam, S.A. Rauscher, R. Seager, H.D. Grissino-Mayer, J.S. Dean, E.R. Cook, C. Gangodagamage, M. Cai, and N.G. McDowell. 2013. Temperature as a potent driver of regional forest drought stress and tree mortality. *Nature Climate Change* 3: 292–297. https://doi.org/10.1038/nclimate1693

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. https://doi.org/10.1002/2015GL064924

Winkler, D.E., J.L. Conver, T.E. Huxman, and D.E. Swann. 2018. The interaction of drought and habitat explain space–time patterns of establishment in saguaro (*Carnegiea gigantea*). *Ecology* 99: 621-631. https://doi.org/10.1002/ecy.2124

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. https://doi.org/10.1016/j.foreco.2016.05.018

Welle, P.D., M.J. Small, S.C. Doney, and I.L. Azevedo. 2017. Estimating the effect of multiple environmental stressors on coral bleaching and mortality. *PLoS One* 12: e0175018. https://doi.org/10.1371/journal.pone.0175018

West, A.M., S. Kumar, T. Wakie, C.S. Brown, T.J. Stohlgren, M. Laituri, and J. Bromberg. 2015. Using high-resolution future climate scenarios to forecast *Bromus tectorum* invasion in Rocky Mountain National Park. *PLoS One* 10: e0117893. https://doi.org/10.1371/journal.pone.0117893

Westerling, A.L., B.P. Bryant, H.K. Preisler, T.P. Holmes, H.G. Hidalgo, T. Das, and S.R. Shrestha. 2011a. Climate change and growth scenarios for California wildfire. *Climatic Change* 109: S445–463. https://doi.org/10.1007/s10584-011-0329-9

Westerling, A.L., M.G. Turner, E.A.H. Smithwick, W.H. Romme, and M.G. Ryan. 2011b. Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. *Proceedings of the National Academy of Sciences of the USA* 108: 13 165–13 170. https://doi.org/10.1073/pnas.1110199108
Zolkos, S.G., P. Jantz, T. Cormier, L.R. Iverson, D.W. McKenney, and S.J. Goetz. 2015. Projected tree species redistribution under climate change: Implications for ecosystem vulnerability across protected areas in the eastern United States. *Ecosystems* **18**: 202–220. https://doi.org/10.1007/s10021-014-9822-0

Young, D.J.N., C.M. Werner, K.R. Welch, T.P. Young, H.D. Safford, and A.M. Latimer. 2019. Post-fire forest regeneration shows limited climate tracking and potential for drought-induced type conversion. *Ecology* **100**: e02571. https://doi.org/10.1002/ecy.2571

Young, D.J.N., J.T. Stevens, J.M. Earles, J. Moore, A. Ellis, A.L. Jirka, and A.M. Latimer. 2017. Long-term climate and competition explain forest mortality patterns under extreme drought. *Ecology Letters* **20**: 78–86. https://doi.org/10.1111/ele.12711