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

SIX

Climate Change Trends, Impacts, and Vulnerabilities in US National Parks

PATRICK GONZALEZ

Introduction

Field measurements have detected glaciers melting in Glacier National Park (Vaughan et al. 2013), sea level rising in Golden Gate National Recreation Area (Church and White 2011), trees dying in Sequoia National Park (van Mantgem et al. 2009), vegetation shifting upslope in Yosemite National Park (Millar et al. 2004) and poleward in Noatak National Preserve (Suarez 1999), wildfire changing in Yellowstone National Park (Littell et al. 2009), and corals bleaching in Virgin Islands National Park (Eakin et al. 2010). Published analyses of these and similar cases around the world have attributed the cause to human-induced climate change (Intergovernmental Panel on Climate Change [IPCC] 2013, 2014a). If we do not reduce greenhouse gas emissions from power plants, cars, and deforestation, continued climate change may fundamentally alter many of the globally unique ecosystems, endangered plant and animal species, and physical and cultural resources that national parks protect.

A growing collection of scientific research focuses specifically on climate change in US national parks. This chapter reviews climate change research published in peer-reviewed journals and IPCC reports that uses data from US national parks. The chapter covers climate trends, historical impacts, and projected vulnerabilities.

Published field research from national parks has contributed to the detection of 20th-century physical and ecological changes and to the attribution of the cause of those changes to human-induced climate change. The section on historical impacts first reviews research that has employed the research procedures of detection and attribution (IPCC 2001a). Detection is the finding of statistically significant changes over time. Attribution is the analysis of the relative weights of different causes and the determination of human-induced climate change as the primary cause. Attribution requires examination of causal factors and a time series of at least 30 years, the minimum statistically significant size for a time series and a period long enough to rule out short-term variations (von Storch and Zwiers 1999).

Detection answers the basic question of whether a species, ecosystem, or other resource is changing. Attribution guides resource management toward the predominant factor that is causing change. Whereas resource managers have developed many actions to address urbanization and other nonclimate factors, changes attributed to human-induced climate change may require new adaptation measures. A subsection in the historical impacts section reviews research that has found other changes that are consistent with, but not formally attributed to, human-induced climate change.

Analyses of climate and resources in US national parks project potential future vulnerabilities to climate change. The section on projected vulnerabilities reviews research that has specifically analyzed national parks. The potential future magnitude of climate change depends on human population size, the magnitude and efficiency of energy use and industrial activity, the extent of deforestation, and feedbacks among climate and biogeochemical cycles. The IPCC has defined greenhouse gas emissions scenarios—discrete sets of potential future conditions that provide standard situations for vulnerability analyses. The most recently updated emissions scenarios are the four representative concentration pathways (RCPs) (Moss et al. 2010; IPCC 2013), ranging from a low emissions scenario (RCP2.6) in an environmentally favorable society to a very high emissions scenario (RCP8.5) due to lack of improvements in practices and policies. General circulation models (GCMs) of the atmosphere provide projections of potential future climate. The two major uncertainties of future climate projections are the extent to which society changes its practices and policies to reduce greenhouse gas emissions and the varying skill among the GCMs to accurately portray spatial and temporal patterns of climate.

Vulnerability is "the propensity or predisposition to be adversely affected" (IPCC 2014a). Three components of vulnerability most relevant to national park resources are exposure, sensitivity, and adaptive capacity (IPCC 2007a). The most effective vulnerability analyses combine historical observations and future projections of climate and resources to identify locations of vulnerable areas and potential refugia and to quantify uncertainties (Gonzalez 2011). In addition to the uncertainties of societal changes to reduce emissions and the varying skill of GCMs, vulnerability analyses are also subject to uncertainty in the accuracy of models used to project responses of species, ecosystems, and other resources to climate change.

Effective vulnerability analyses provide spatial data for prioritizing the location of future adaptation measures.

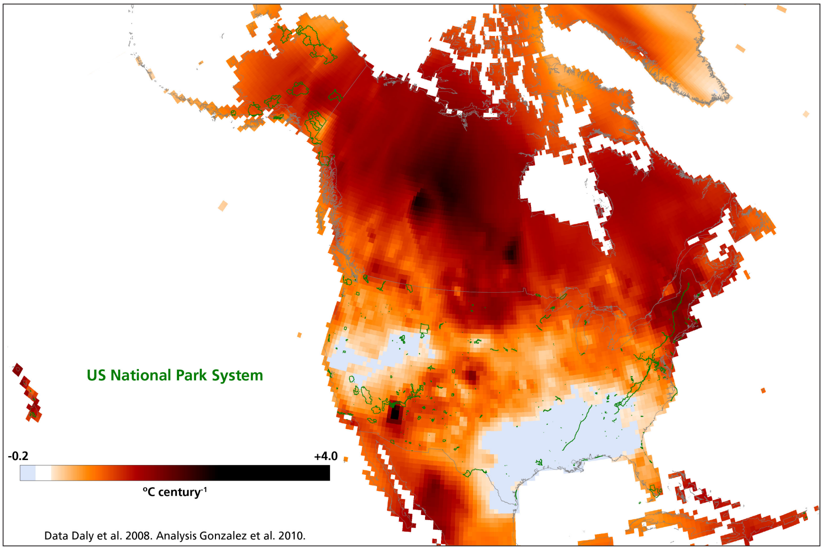
Historical Impacts

Climate Trends

Analyses of weather station measurements have detected a statistically significant increase of global temperature and other climate changes since the beginning of the instrumental record in 1850, and the analyses of causal factors have attributed the cause to an increase of atmospheric concentrations of carbon dioxide (CO_2) and other greenhouse gases emitted from power plants, cars, deforestation, and other human sources (IPCC 2013). Analyses of spatial data interpolated from weather stations (Daly et al. 2008) show that the average annual temperature of the area of the US National Park System (this chapter refers to the 410 national parks existing in April 2016) increased at a statistically significant rate of 0.9 °C ±0.2 °C per century (mean ±SE) from 1895 to 2010, with 96% of system area experiencing increases and two-thirds experiencing statistically significant increases (F. Wang et al., unpublished data). In the 20th century, the National Park System experienced heating at a rate three times greater than the United States as a whole (fig. 6.1), mainly because 60% of National Park System area is in Alaska and temperature increases have been greater at higher latitudes (IPCC 2013).

For a sample of the largest national parks and 30 km buffer zones around those parks, average annual temperature increased at rates greater than 1 °C per century from 1895 to 2009 (Hansen et al. 2014), and temperature from 1982 to 2012 was higher than other periods from 1901 to 2012 (Monahan and Fisichelli 2014). Some smaller national parks in the southeastern United States lie in an anomalous area where temperature has not increased because of local cooling effects of increased precipitation, the El Niño–Southern Oscillation, and other factors (Portmann, Solomon, and Hegerl 2009).

Because warmer air can hold more moisture, climate change has been increasing precipitation globally (IPCC 2013). In the United States as a whole, precipitation increased at a statistically significant rate of +4% ±2% per century from 1895 to 2010, with only one-fifth of the area experiencing decreases (F. Wang et al., unpublished data). In contrast, total annual precipitation of the area of the National Park System decreased at a rate of −2% ±2% per century from 1895 to 2010, with half of system area experiencing decreases and 16% experiencing statistically significant changes.



6.1. Trend in average annual temperature, from linear regression, 1901–2002 (Daly et al. 2008; Gonzalez et al 2010).

Across the western United States, 53 national parks host National Weather Service stations that have contributed data to the detection of global climate change in the last half of the 20th century and to the attribution to human emissions. Changes in climate in the western United States include increases in winter minimum temperatures at rates of 2.8 °C to 4.3 °C per century (Barnett et al. 2008; Bonfils et al. 2008), decreases in ratio of snow to rain at rates of −24% to −79% per century (Barnett et al. 2008; Bonfils et al. 200), and an advance of spring warmth of one week from 1950 to 2005 (Ault et al. 2011).

Weather stations in national parks across the United States that are part of the Global Historical Climatology Network have contributed to the global detection of extreme temperature and precipitation events. In the United States, the number of warm nights per year (minimum daily temperature greater than the 90th percentile) increased by up to 20 days from 1951 to 2010 (IPCC 2013). In the northeastern United States, total annual precipitation falling in heavy storms (daily precipitation greater than the 95th percentile) increased by 50% from 1951 to 2010 (IPCC 2013).

National parks on the Atlantic and Pacific coasts lie in the path of tropical cyclones (also called hurricanes). Although historical observations show an increase in the intensity of North Atlantic hurricanes after

1970, changing historical methods, incomplete understanding of physical mechanisms, and tropical cyclone variability prevent direct attribution to climate change (IPCC 2012, 2013).

Physical Impacts

Field data from numerous national parks have contributed to detection of physical changes and to attribution to human-induced climate change (table 6.1). Measurements from National Weather Service stations in 53 western national parks and from Natural Resources Conservation Service snow courses in many of those parks contributed to detection of decreased snowpack (Barnett et al. 2008; Pierce et al. 2008) and advances of spring stream flow of one week (Barnett et al. 2008). Analyses of snow measurements and tree rings from across the western United States, including sites in nine national parks, detected snowpack levels in the 20th century lower than any time since the 13th century and attributed the low snowpack to human-induced climate change (Pederson et al. 2011).

IPCC analyses of measurements of 168,000 glaciers around the world, including glaciers in Denali National Park and Preserve, Glacier National Park, Glacier Bay National Park and Preserve, Kenai Fjords National Park, Lake Clark National Park and Preserve, North Cascades National Park, and Wrangell–Saint Elias National Park and Preserve, have detected decreases in length, area, volume, and mass for almost all the glaciers since 1960 (Vaughan et al. 2013). The IPCC has shown that the cause is attributable to human-induced climate change more than natural variation or other non-human factors (Bindoff et al. 2013). Further analyses confirm that the loss of mass from Alaskan and western North American glaciers in the period 1960–2010 is attributable to human-induced climate change (Marzeion et al. 2014). In Glacier National Park, Agassiz Glacier receded 1.5 km from 1926 to 1979 (Pederson et al. 2004). In Glacier Bay National Park and Preserve, the greatest ice loss has occurred from Muir Glacier, which lost 640 m in its lower reaches from 1948 to 2000 (Larsen et al. 2007) (fig. 6.2).

Analyses of tidal gauge measurements around the world have detected a statistically significant rise in global sea level (Church and White 2011; Church et al. 2013), with IPCC analyses of potential causal factors attributing the rise to human-induced climate change (Bindoff et al. 2013). Golden Gate National Recreation Area in San Francisco, California, hosts the tidal gauge with the longest time series in the Western Hemisphere, operated by the National Oceanic and Atmospheric Administration (NOAA). Sea level there rose at a statistically significant rate of 14 cm ±0.8 cm per

Table 6.1 Historical changes detected in US national parks and attributed to human-induced climate change

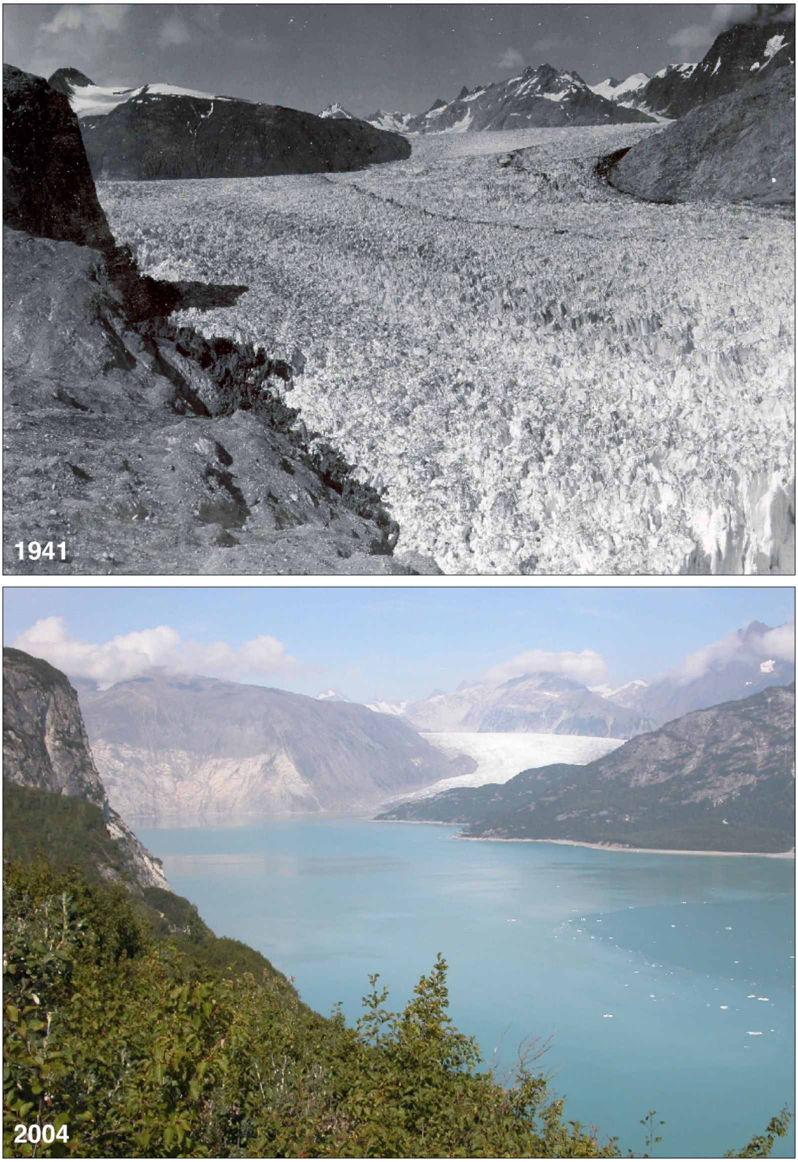
Resource	Impact	National park	Years	Reference
Physical				
Glaciers	Decreased length, area, volume, and mass of most glaciers	Global; Denali NP, Glacier NP, Glacier Bay NP Pres., Kenai Fjords NP, Lake Clark NP Pres., North Cascades NP, Wrangell–Saint Elias NP Pres.	1960–2012	IPCC 2013; Marzeion et al. 2014
	Disappearance of 4 glaciers, thinning of 12 glaciers by 6 m	Lake Chelan NRA, North Cascades NP, Ross Lake NRA	1984–2004	Pelto 2006; IPCC 2013
	Recession of Agassiz Glacier by 1.5 km, recession of Jackson Glacier by 1 km	Glacier NP	1926–1979	Pederson et al. 2004; IPCC 2013
	Recession of Toklat River glaciers greater than 400 m, thinning 5–6 m year^{-1}	Denali NP	2000–2009	Crossman, Futter, Whitehead 2013; IPCC 2013
	Reduction in total area of 7%	Lake Chelan NRA, North Cascades NP, Ross Lake NRA	1958–1998	Granshaw and Fountain 2006; IPCC 2013
	Reductions in area among 30 glaciers up to 40%	Rocky Mountain NP	1888–2005	Hoffman, Fountain, and Achuff 2007; IPCC 2013
	Thinning up to 7.5 m year^{-1}	Wrangell–Saint Elias NP Pres.	2000–2007	Arendt et al. 2008; IPCC 2013
	Thinning up to 640 m	Glacier Bay NP Pres.	1948–2000	Larsen et al. 2007; IPCC 2013
Sea level	Rise 17 cm ±2 cm century^{-1}	Global; Golden Gate NRA	1901–2010	Church and White 2011; IPCC 2013
	Rise 1–37 cm century^{-1}	19 Atlantic and Pacific coast NPs	1854–1999	Pendleton, Thieler, and Williams 2010; IPCC 2013
Sea temperatures	Increase 1.1°C ±0.2°C century^{-1}	Global; Buck Island Reef NM, Channel Islands NP, Virgin Islands Coral Reef NM	1971–2010	IPCC 2013
	Increase ~0.8°C century^{-1}	Biscayne NP	1878–2012	IPCC 2013; Kuffner et al. 2015

(*continued*)

Table 6.1 (*continued*)

Resource	Impact	National park	Years	Reference
Snowpack	Decrease to lowest extent in 8 centuries	Western United States; 9 NPs	1200–2000	Pederson et al. 2011
	Decrease up to 8% decade^{-1}	Western United States; 50+ NPs	1950–1999	Barnett et al. 2008; Pierce et al. 2008
Streams	Peak stream flow advance up to 1.7 days decade^{-1}	Western United States; 50+ NPs	1950–1999	Barnett et al. 2008
Ecological				
Biomes	Shift northward of boreal conifer forest into tundra 80–100 m	Noatak N. Pres.	1700–1990	Suarez et al. 1999
	Shift upslope of subalpine forest into alpine meadows	California; Yosemite NP	1880–2002	Millar et al. 2004
Birds	Shift northward of winter ranges of 254 species 0.5 km ±0.3 km year^{-1}	Contiguous United States; 50+ NPs	1975–2004	La Sorte and Thompson 2007
Corals	Bleaching of corals due to highest temperatures in the period 1855–2008	Caribbean Sea; Biscayne NP, Buck Island Reef NM, Salt River Bay NHP and Ecological Pres., Virgin Islands NP, Virgin Islands Coral Reef NM	2005	Eakin et al. 2010; IPCC 2014a
Insect pests	Bark beetles in the largest outbreak in time period	Western United States; Yellowstone NP, other NPs	1880–2005	Raffa et al. 2008; Logan, Macfarlane, and Willcox 2010; Macfarlane, Logan, and Kern 2013
Mammals	Shift upslope of ranges of half of 28 small mammal ranges ~500 m	Yosemite NP	1914–1920	Moritz et al. 2008
Trees	Mortality doubled in old conifer forests	Kings Canyon NP, Lassen Volcanic NP, Mount Rainier NP, Rocky Mountain NP, Sequoia NP, Yosemite NP	1955–2007	van Mantgem et al. 2009
Wildfire	Climate dominant factor controlling burned area	Western United States; NPs	1916–2003	Littell et al. 2009

Note: NHP = National Historical Park; NHS = National Historic Site; NL = National Lakeshore; NM = National Monument; NP = National Park; NP Pres. = National Park and Preserve; N. Pres. = National Preserve; NRA = National Recreation Area; NS = National Seashore.



6.2. Muir Glacier, Glacier Bay National Park and Preserve, Alaska: August 13, 1941 (photo by William O. Field, courtesy of the National Park Service, National Snow and Ice Data Center, and US Geological Survey), and August 31, 2004 (photo by Bruce F. Molnia, courtesy of the US Geological Survey). IPCC has analyzed a global database of 168,000 glaciers, including Muir Glacier, and attributed melting since the 1960s to human-induced climate change (Bindoff et al. 2013; Vaughan et al. 2013).

century from 1855 to 2014. At the NOAA tidal gauge in Washington, DC, not far from the Jefferson Memorial and numerous other national parks in the capital, sea level rose at a rate of 31 cm ±1 cm per century from 1931 to 2013. Sea level has been rising at rates of up to 37 cm per century in 19 national parks along the Atlantic and Pacific coasts (Pendleton, Thieler, and Williams 2010).

Global measurements of sea surface temperatures, including measurements in Buck Island Reef National Monument, Channel Islands National Park, and Virgin Islands Coral Reef National Monument, have detected an increase in the top 75 m of ocean water of 1.1°C ±0.2°C per century from 1971 to 2010 (Rhein et al. 2013), with IPCC analyses attributing the cause to human-induced climate change (Bindoff et al. 2013). In 1878, the US government built Fowey Rocks Lighthouse in the Florida Keys in what would later become Biscayne National Park. Comparison of sea surface temperatures taken by lighthouse keepers from 1879 to 1912 with measurements by electronic sensors from 1991 to 2012 showed a statistically significant warming of ~0.8°C per century (Kuffner et al. 2015). Summer sea surface temperatures from 1991 to 2012 exceeded 29°C, a threshold of stress for many coral species.

Increased atmospheric CO_2 concentrations from human activities have increased the acidity of ocean water around the world by 0.1 pH units since ~1750 (Rhein et al. 2013). Ocean acidification occurs when CO_2 dissolves in water and forms carbonic acid. High acidity can dissolve the shells of many marine species. Research on past acidification in national parks has not been published.

Ecological Impacts

Field data from numerous national parks have contributed to detection of ecological changes and attribution to human-induced climate change (see table 6.1). Vegetation at the level of the biome (10–15 major global vegetation types) has shifted upslope or toward the poles or the equator at sites around the world, and analyses of possible causes have attributed most of the shifts to human-induced climate change (Gonzalez et al. 2010; Settele et al. 2014). In Noatak National Preserve, Alaska, boreal conifer forest shifted northward 80–100 m into tundra between 1800 and 1990 (Suarez et al. 1999). In Yosemite National Park, subalpine forest shifted upslope into alpine meadows between 1880 and 2002 (Millar et al. 2004).

Multivariate analysis of wildfire across the western United States from 1916 to 2003, using data from numerous national parks and other areas, indicates that climate was the dominant factor controlling the extent of burned area, even during periods of active fire suppression (Littell et al. 2009). Reconstruction of fires of the past 400 to 3,000 years in the western United States (Trouet et al. 2010; Marlon et al. 2012) and in Sequoia and Yosemite National Parks (Swetnam 1993; Swetnam et al. 2009; Taylor and Scholl 2012) confirms that temperature and drought are the dominant factors explaining fire occurrence.

Field and remote sensing data from across western North America, including numerous national parks, have also documented how climate change has caused bark beetle outbreaks leading to the most extensive tree mortality across western North America in the last 125 years (Raffa et al. 2008). Tracking of trees in permanent old-growth conifer forest plots across the western United States, including plots in Kings Canyon, Lassen Volcanic, Mount Rainier, Rocky Mountain, Sequoia, and Yosemite National Parks, found a statistically significant doubling of tree mortality between 1955 and 2007 (van Mantgem et al. 2009). Analyses of fire, mortality of small trees, forest fragmentation, air pollution, and climate attributed the mortality to warming due to climate change.

Climate change has caused shifts in latitude or elevation of the ranges of numerous animal species around the world (Settele et al. 2014). In Yosemite National Park, small mammal resurveys in 2006 of the Grinnell surveys from 1914 to 1920 showed that the ranges of half of 28 small mammal species shifted upslope an average of ~500 m (Moritz et al. 2008). Because the national park had protected the survey transect, land-use change or other factors were not major factors. Therefore, the authors could attribute the shift to a 3°C increase in minimum temperature caused by climate change. Analyses of Audubon Christmas Bird Count data across the United States, including sites in 54 national parks, detected a northward shift of winter ranges of a set of 254 bird species at an average rate of 0.5 km ±0.3 km per year from 1975 to 2004, attributable to human-induced climate change (La Sorte and Thompson 2007). Examples include northward shifts of the Evening Grosbeak (*Coccothraustes vespertinus*) in Shenandoah National Park and the Canyon Wren (*Catherpes mexicanus*) in Santa Monica Mountains National Recreation Area.

High ocean temperatures due to climate change have bleached and killed coral around the world (Wong et al. 2014). In 2005, the hottest sea surface temperatures recorded in the Caribbean Sea in the period 1855–2008 caused coral bleaching and the death of up to 80% of coral area at sites in Biscayne National Park, Buck Island Reef National Monument, Salt River Bay National Historical Park and Ecological Preserve, Virgin Islands

National Park, and Virgin Islands Coral Reef National Monument (Eakin et al. 2010).

Other Changes Consistent with, but Not Attributed to, Climate Change

Researchers have observed other 20th-century changes to resources in national parks that have not been explicitly attributed to human-induced climate change but are consistent with responses to climate change (table 6.2). The most prominent physical change is melting of permafrost in Alaskan national parks (Riordan, Verbyla, and McGuire 2006; Jones et al. 2011; Necsoiu et al. 2013; Balser, Jones, and Gens 2014). Ecological changes include upslope shifts of forests into alpine meadows, vegetation dieback in areas of increased aridity, changes to amphibians, range shifts of birds, and declines of mammal species. Changes in phenology include advances of cherry tree (*Prunus* × *yedoensis*) blooming in Washington, DC (Abu-Asab et al. 2001), White-tailed Ptarmigan (*Lagopus leucurus*) hatching in Rocky Mountain National Park (Wang et al. 2002), and loggerhead sea turtle (*Caretta caretta*) nesting in Canaveral National Seashore (Pike, Antworth, and Stiner 2006). One change in cultural resources has occurred in Wrangell–Saint Elias and Lake Clark National Parks and Preserves, where melting glaciers are revealing archaeological artifacts, such as wooden arrow shafts and a birch bark basket fragment, dating from circa 500 to 1770 (Dixon, Manley, and Lee 2005; VanderHoek et al. 2012).

Future Vulnerabilities

Climate Projections

Spatial analyses of the output of the 33 GCMs used by the IPCC (2013) provide climate projections for the area of the National Park System. The ensemble of GCMs projects an average annual temperature increase (1971–2000 to 2071–2100) of 2.2 °C ±0.9 °C per century (mean ±SD) under RCP2.6, and 5.6 °C ±1.3 °C per century under RCP8.5 (F. Wang et al., unpublished data). This potential 21st-century heating would be two to six times the magnitude of historical 20th-century warming. Temperature projections are highest for the national parks in Alaska, with projected increases up to 10 °C per century under RCP8.5.

The ensemble of GCMs projects a total annual precipitation increase (1971–2000 to 2071–2100) of 9% ±13% per century (mean ±SD) under RCP2.6, and 21% ±5% per century under RCP8.5 (F. Wang et al.,

Table 6.2 Changes in US national parks consistent with, but not formally attributed to, climate change

Resource	Change	National park	Years	Reference
Physical				
Permafrost	Contraction of ponds due to draining	Denali NP Pres., Wrangell–Saint Elias NP Pres.	1950–2002	Riordan et al. 2006
	Melting edges and contraction of water bodies due to draining	Kobuk Valley NP	1951–2005	Necsoiu et al. 2013
	Thaw and retrogressive thaw slump initiation	Noatak N. Pres.	1992–2011	Balser, Jones, and Gens 2014
	Thermokarst lakes increased in number and decreased in surface area due to draining	Bering Land Bridge N. Pres.	1950–2007	Jones et al. 2011
Streams	Beetle kill increased, forest cover decreased, groundwater contributions to streams increased	Rocky Mountain NP	1994–2012	Bearup et al. 2014
	Stream nitrate concentration increased as glacial melt exposed sediments	Rocky Mountain NP	1991–2006	Baron et al. 2009
Plants				
Biomes	Shift northward of mangrove forest	Biscayne NP, Canaveral NS	1984–2011	Cavanaugh et al. 2014
	Shift upslope of piñon-juniper woodland (*Pinus edulis*, *Juniperus monosperma*) into ponderosa pine forest (*Pinus ponderosa*)	Bandelier NM	1935–1975	Allen and Breshears 1998
	Shift upslope of subalpine forest	California; Yosemite NP	1929–2009	Dolanc, Thorne, and Safford 2013
		Glacier NP	1945–1991	Klasner and Fagre 2002
		Glacier NP	1925–2003	Roush, Munroe, and Fagre 2007
		Lassen Volcanic NP	1840–1990	Taylor 1995
	Shift upslope of subalpine forest into alpine meadows	Mount Rainier NP	1916–1969	Franklin et al. 1971
		Mount Rainier NP	1930–1990	Rochefort and Peterson 1996

(*continued*)

Table 6.2 (*continued*)

Resource	Change	National park	Years	Reference
Plants				
		Olympic NP	1905–1991	Woodward, Schreiner, and Silsbee. 1995
		Rocky Mountain NP	1930–1990	Hessl and Baker 1997
	Shift upslope of temperate conifer forest into subalpine meadows	Yellowstone NP	1860–1986	Jakubos and Romme 1993
Plants, nonwoody	Alpine plants declined at high elevation	Glacier NP	1988–2011	Lesica and McCune 2004; Lesica 2014
	Haleakala silversword (*Argyroxyphium sandwicense macrocephalum*) decreased as rainfall decreased	Hawai'i; Haleakala NP	1982–2010	Krushelnycky et al. 2013
	Herb and forb species of cool habitats declined	Oregon; Oregon Caves NM Pres.	1949–2007	Whittaker 1960; Damschen, Harrison, and Grace 2010
	Joshua tree (*Yucca brevifolia*) mortality due to wildfire in invasive grasses, drought, and gnawing by rodents	Joshua Tree NP	2000–2004	DeFalco et al. 2010
	Soft-leaved paintbrush (*Castilleja mollis*) growth reduced as growing-season temperatures increased	Channel Islands NP	1995–2006	McEachern et al. 2009
Shrubs, nonwoody plants	Herbaceous plants declined with increasing temperatures, but some shrubs increased	Arches NP, Canyonlands NP, Natural Bridges NM	1989–2009	Munson, Belnap, and Okin 2011; Munson et al. 2011
Trees	Cherry tree (*Prunus* × *yedoensis*) blooming advanced 7 days	Washington, DC; Baltimore, MD; National Capital Parks, Rock Creek Park	1970–1999	Abu-Asab et al. 2001
	Conifer growth increased since 1950 at high elevation	California; Yosemite NP	1000–1990	Bunn, Graumlich, and Urban 2005
		Lake Clark NP Pres.	1769–2003	Driscoll et al. 2005
	Large trees declined, small trees increased, and oak (*Quercus* spp.) increased as climate water deficit increased	Kings Canyon NP, Sequoia NP, Yosemite NP	1929–2010	McIntyre et al. 2015

	Quaking aspen (*Populus tremuloides*) recruitment decreased by increased browsing as snowpack decreased	Yellowstone NP	2007–2009	Brodie et al. 2012
	Tree dieback after years of drought	Southwestern United States; Bandelier NM	2002–2003	Breshears et al. 2005
	Tree dieback with 38% decrease of crown area after years of drought	Bandelier NM	2002–2011	Garrity et al. 2013
Wetlands	Wetland vegetation increased and dryland vegetation decreased as sea level rose	Gulf Islands NS	1978–2004	Lucas and Carter 2010
Wildfire	Burned area increased	Alaska; NPs	1860–2009	Kasischke et al. 2010
	Burned area related to temperature increase and rainfall decrease	Yellowstone NP	1895–1989	Balling, Meyer, and Wells 1992
	Fire frequency and burned area increased with temperature	Western United States; NPs	1970–2003	Westerling et al. 2006
Animals				
Amphibians	Ranavirus outbreaks related to temperature and other factors	Acadia NP	1999–2005	Gahl and Calhoun 2010
	Salamander body sizes reduced as metabolic requirements increased	Catoctin Mountain Park, Great Smoky Mountains NP, Shenandoah NP	1950–2012	Caruso et al. 2014
	Species richness declined due to wetland desiccation	Yellowstone NP	1992–2008	McMenamin, Hadly, and Wright 2008
Birds	Elevation shift of ranges tracked temperature and precipitation	Lassen Volcanic NP, Sequoia NP, Yosemite NP	1911–2008	Tingley et al. 2009; Tingley et al. 2012
	Shift northward of ranges of 26 species 2.4 km $year^{-1}$	Eastern United States; NPs	1967–2002	Hitch and Leberg 2007
	White-tailed Ptarmigan (*Lagopus leucurus*) hatching advanced 15 days	Rocky Mountain NP	1975–1999	Wang et al. 2002
Corals	Increased prevalence of white pox and other diseases after bleaching	Virgin Islands NP	2004–2006	Muller et al. 2008
Mammals	Belding's ground squirrel (*Urocitellus beldingi*) extirpated from 42% of sites as snow cover decreased	Lassen Volcanic NP, Yosemite NP	1902–2011	Morelli et al. 2012
	Harbor seal (*Phoca vitulina richardii*) population declined as glacial ice calved from tidewater glaciers (used for resting and raising pups) declined	Glacier Bay NP Pres.	1992–2008	Womble et al. 2010

(*continued*)

Table 6.2 (*continued*)

Resource	Change	National park	Years	Reference
Animals				
	Small mammals shifted ranges upslope or downslope in at least one of three regions for 25 of 34 species analyzed, with temperature the main factor explaining changes in high-elevation species range shifts	Kings Canyon NP, Lassen Volcanic NP, Sequoia NP, Yosemite NP	1911–2010	Rowe et al. 2015
	Squirrel body size increased as food plant growing season lengthened	Lassen Volcanic NP, Sequoia NP, Yosemite NP	1902–2008	Eastman et al. 2012
Mussels	Species richness declined as water warmed	California; Channel Islands NP	1968–2002	Smith, Fong, and Ambrose 2006
Reptiles	Loggerhead sea turtle (*Caretta caretta*) nesting advanced 1 week as water temperatures warmed	Canaveral National NS	1989–2003	Pike et al. 2006
Cultural				
Archaeological artifacts	Antler projectile points, wooden arrow shafts, a birch bark basket fragment, a caribou calf hide, and other artifacts from ca. 500 to 1770 exposed by melting glaciers	Lake Clark NP Pres., Wrangell–Saint Elias NP Pres.	2000–2010	Dixon, Manley, and Lee 2005; VanderHoek et al. 2012

Note: See table 6.1 abbreviations. NM Pres. = National Monument and Preserve.

unpublished data). Because of the limited skill of GCMs in projecting precipitation, GCMs disagree on the direction of projected precipitation change (increase or decrease) across much of the National Park System. The projections show more than 80% agreement for the system as a whole, although half of the GCMs project precipitation increases and half project decreases in some national parks in the southwestern United States, California, and Florida. Based on GCM ensemble averages, precipitation may decrease on ~5% of system area. In general, projected precipitation outside the tropics increases with distance from the equator (IPCC 2013).

GCMs project increased frequency and severity of extreme climate events. In North America, the maximum temperature of days so hot that they occur only once every 20 years (1981–2000) may increase by 2°C to 6°C by 2100 (IPCC 2012). In North America, the type of storm with precipitation so heavy that it has occurred only once in 20 years (1981–2000) may increase in frequency to once in 5 to 10 years by 2100 (IPCC 2012). Projections of North Atlantic hurricanes and Pacific tropical cyclones under climate change do not agree on the direction of future trends (IPCC 2013).

Vulnerabilities of Physical Resources

Analyses project potential future vulnerabilities to climate change of air quality, glaciers, permafrost, lake and groundwater levels, and river and stream flows in numerous national parks (table 6.3). In Glacier National Park, Hall and Fagre (2003) estimated that a temperature increase of 1°C could lead to complete melting of glaciers, which, at a rate of 3.3°C per century, could occur as early as 2030. Nineteen national parks on the Atlantic and Pacific coasts are vulnerable to inundation and coastal erosion from sea-level rise and storm surges (Pendleton, Thieler, and Williams 2010). Grand Canyon and Big Bend National Parks are vulnerable to lower river flows because of increased aridity and human water withdrawals.

Vulnerabilities of Plants

Analyses project potential future vulnerabilities to climate change of vegetation in numerous national parks (see table 6.3). National parks are vulnerable to northward and upslope vegetation shifts, with 16%–41% of National Park System area highly vulnerable to biome shifts (Gonzalez et al. 2010), and 4%–31% of system area highly vulnerable to the combination of biome shifts due to climate change and habitat fragmentation due to roads, urbanization, and agriculture (Eigenbrod et al. 2015) (fig. 6.3).

Table 6.3 Future vulnerabilities to projected climate change of resources in US national parks

Resource	Vulnerability	National park	Scenario	Reference
Physical				
Air quality	Nitrogen deposition from motor vehicles and other sources exceeds critical loads	17–25 NPs nationwide	RCP2.6, RCP8.5	Ellis et al. 2013
Coasts	Coastal and lakeshore parks moderately vulnerable overall, Atlantic and Gulf of Mexico parks highly vulnerable	22 NPs on ocean coasts and Great Lakes shores	Water level −57 to +37 cm $century^{-1}$	Pendleton, Thieler, and Williams 2010
	Inundation of one-quarter of the area	Cape Cod NS	Sea level +1–2 m	Murdukhayeva et al. 2013
	Inundation of one-third of the area	Assateague Island NS	Sea level +0.6–2 m	Murdukhayeva et al. 2013
Glaciers	Complete disappearance as early as 2030	Glacier NP	CO_2 doubling	Hall and Fagre 2003
	Sperry Glacier, 80% volume reduction by 2100 (min.), disappearance by 2040 (max.)	Rocky Mountain NP	+1 °C–10 °C	Brown, Harper, and Humphrey 2010
	Toklat River glaciers melt 2–11 m	Denali NP	B2, A2	Crossman, Futter, Whitehead 2013
Lakes	Lake Mead decrease to 7 m above dead storage (water level of lowest intake) 2%–9% probability by 2035	Lake Mead NRA	B1, A1B, A2	Dawadi and Ahmad 2012
	Lakes Mead and Powell, 50% chance of loss of live storage (min. water level for hydroelectric production) by 2021	Glen Canyon NRA, Lake Mead NRA	Runoff −20%	Barnett and Pierce 2008
Permafrost	Reduction of area 40%–100%	Rocky Mountain NP	+0.5 °C–4 °C	Janke 2005
Rivers	Colorado River flow change of −42% to +18%	Arizona, California, Colorado, Mexico; Glen Canyon NRA, Grand Canyon NP, Lake Mead NRA	A2	US Bureau of Reclamation 2012; Vano et al. 2014
	Rio Grande flow reduction	Mexico, Texas; Big Bend NP, Rio Grande WSR	B1, A1B, A2	US Bureau of Reclamation 2013

Streams	Spring runoff decline 15%–27%, advance spring runoff 4–6 weeks by 2080	Glacier NP	B1, A1F1	Larson et al. 2011
Water table	Water table decrease up to 1.1 m	Everglades NP	+1.5 °C, precipitation ±10%, sea level +46 cm	Nungesser et al. 2015
Plants				
Biomes	Shift northward and upslope, high vulnerability of 16%–41% of National Park System area	Global; US National Park System	B1, A1B, A2	Gonzalez et al. 2010; Eigenbrod et al. 2015
	Shift northward and upslope, together with habitat fragmentation, high vulnerability of 4%–31% of National Park System area	Global; US National Park System	B1, A1B, A2	Eigenbrod et al. 2015
	Shift northward of boreal forest into tundra	Alaska; Bering Land Bridge N. Pres.	+2 °C–4 °C	Rupp, Chapin, and Starfield 2000
	Shift northward of boreal forest into tundra	Alaska; Kobuk Valley NP, Noatak N. Pres.	+2 °C–4 °C	Rupp, Chapin, and Starfield 2001
	Shift upslope of temperate conifer forest into subalpine forest into alpine meadows	Olympic NP	+2 °C, precipitation ±20%	Zolbrod and Peterson 1999
Plants, nonwoody	Hoffmann's slender-flowered gilia (*Gilia tenuiflora* ssp. *hoffmannii*), Northern Channel Island phacelia (*Phacelia insularis* var. *insularis*), and Santa Cruz Island chicory (*Malacothrix indecora*) germination reduction with higher temperatures after first rains	Channel Islands NP	HS	Levine, McEachern, and Cowan 2008
	Joshua tree (*Yucca brevifolia*) up to 90% loss of habitat, no refugia in Joshua Tree NP	Southwestern United States; Death Valley NP, Joshua Tree NP, Mojave N. Pres., Tule Springs Fossil Beds NM	A1B	Cole et al. 2011
	Joshua tree (*Yucca brevifolia*) up to 90% loss of habitat, some refugia in Joshua Tree NP	Joshua Tree NP	+3 °C	Barrows and Murphy-Mariscal 2012

(*continued*)

Table 6.3 (*continued*)

Resource	Vulnerability	National park	Scenario	Reference
Plants				
Polar vegetation	Vegetation type change of 6%–17% of land area	Bering Land Bridge N. Pres., Cape Krusenstern NP, Gates of the Arctic NP Pres., Kobuk Valley NP, Noatak N. Pres.	A1B (6 °C)	Jorgenson et al. 2015
Trees, invasive	Tree-of-heaven (*Ailanthus altissima*) habitat increase 48%	Appalachian Trail	RCP6.0	Clark, Wang, and August 2014
Trees	Bishop pine (*Pinus muricata*) requires water from fog and the cooling effect of overcast skies	Channel Islands NP	HS	Fischer, Still, and Williams 2009; Carbone et al. 2013
	Cherry tree (*Prunus* × *yedoensis*) peak bloom advance of 1 week to 1 month	National Capital Parks	A1B, A2	Chung et al. 2011
	Coastal scrub vegetation reduction	Point Reyes NS	A1B, A2	Hameed et al. 2013
	Douglas-fir (*Pseudotsuga menziesii*) growth reduction; mountain hemlock (*Tsuga mertensiana*) and subalpine fir (*Abies lasiocarpa*) growth increase	Mount Rainier NP, North Cascades NP, and Olympic NP	B1, A1B	Albright and Peterson 2013
	Eastern US trees, 134 species, habitat change for one-fourth to three-fourths	121 eastern US NPs	B1, A1FI	Fisichelli et al. 2014
	Foothills palo verde (*Parkinsonia microphylla*), ocotillo (*Fouquieria splendens*), and creosote bush (*Larrea tridentata*) increased mortality	Organ Pipe Cactus NM, Saguaro NP	HS	Munson et al. 2012
	Limber pine (*Pinus flexilis*) upslope range contraction	Rocky Mountain NP	RCP4.5, RCP8.5	Monahan et al. 2013
	Quaking aspen (*Populus tremuloides*) habitat reduction 46%–94%	Yellowstone NP	B1, B2, A2	Rehfeldt, Ferguson, and Crookston 2009
	Single-leaf piñon (*Pinus monophylla*) and California juniper (*Juniperus californica*) habitat reduction	Joshua Tree NP	+3 °C	Barrows et al. 2014

	Torrey pine (*Pinus torreyana* ssp. *insularis*) requires water from fog and the cooling effect of overcast skies	Channel Islands NP	HS	Williams et al. 2008
	Tree dieback	Southwestern United States; Bandelier NM	A2	Williams et al. 2013
	Tropical montane cloud forests sensitive to drought	Hawai'i; Haleakala NP	HS	Loope and Giambelluca 1998
	Western white pine (*Pinus monticola*) and mountain hemlock (*Tsuga mertensiana*) increase in climate water deficit	Yosemite NP	B1 (1.5 °C)	Lutz, Wagtendonk, and Franklin 2010
	Whitebark pine (*Pinus albicaulis*) habitat reduction 71%–99%	Greater Yellowstone Ecosystem; Grand Teton NP, John D. Rockefeller Jr. Memorial Parkway, Yellowstone NP	RCP4.5, RCP8.5	Chang, Hansen, and Piekielek 2014
Wetlands	Buttonwood (*Conocarpus erectus*), mahogany (*Swietenia mahagoni*), and other species killed by saltwater intrusion	Everglades NP	Sea level +10 cm	Saha et al. 2011
	Mangrove forests soil accumulation too low, eroded soil affects benthic habitats	Everglades NP	+1.5 °C, precipitation ±10%, sea level +46 cm	Koch et al. 2015
	Sawgrass decrease with decreased precipitation	Everglades NP	B1, A1B, A2	Todd et al. 2012
	Tall sawgrass and pine savanna more strongly affected than sawgrass	Everglades NP	Inundation time +30% to −60%	Foti et al 2013
	Wetland or upland vegetation decrease, depending on precipitation	Everglades NP	+1.5 °C, precipitation ±10%, sea level +46 cm	van der Valk, Volin, and Wetzel 2015
Wildfire	Fire frequency increase 3 to 10 times historical frequencies	Yellowstone NP	A2	Westerling et al. 2011

(*continued*)

Table 6.3 (*continued*)

Resource	Vulnerability	National park	Scenario	Reference
Animals				
Amphibians	Mountain pond habitat reduction	Washington; Mount Rainier NP, North Cascades NP, Olympic NP	A1B	Ryan et al. 2014
Birds	Habitat decline for half of 162 species	Bering Land Bridge N. Pres., Cape Krusenstern NP, Gates of the Arctic NP Pres., Kobuk Valley NP, Noatak N. Pres.	A1B	Marcot et al. 2015
	Loggerhead Shrike (*Lanius ludovicianus*), Scaled Quail (*Callipepla squamata*), and Rock Wren (*Salpinctes obsoletus*) ranges shift from desert and grassland to shrubland	Big Bend NP	A1FI	White et al. 2011
	Northern Spotted Owl (*Strix occidentalis caurina*) survival decreases in areas of warmer, wetter winters and hotter, drier summers	Oregon, Washington; Olympic NP	HS	Glenn et al. 2011
	Rufa Red Knot (*Calidris canutus rufa*) endangered by habitat reduction from sea-level rise, prey reduction from heat mortality, phenology mismatch of Red Knot migration and prey availability	Atlantic Coast, Gulf of Mexico; NPs	HS	US Department of the Interior 2014
	Wading bird habitat reduced under drier scenarios	Everglades NP	+1.5°C, precipitation ±10%, sea level +31 cm	Catano et al. 2015
	White-tailed Ptarmigan (*Lagopus leucurus*) population reduction by half	Rocky Mountain NP	+2°C–3°C	Wang et al. 2002
Corals	Coral early life-phases particularly susceptible to ocean acidification	Dry Tortugas NP	HS	Kuffner, Hickey, and Morrison 2013
	Corals vulnerable to bleaching but show some tolerance and adaptive capacity	NP of American Samoa	HS	Craig, Birkeland, and Belliveau 2001; Oliver and Palumbi 2009; Palumbi et al. 2014

Fish	Devil's Hole pupfish (*Cyprinodon diabolis*) favorable spawning conditions reduction up to 2 weeks	Death Valley NP	RCP2.6, RCP4.5, RCP6.0, RCP8.5	Hausner et al. 2014
	Freshwater fish reduced abundance from advanced spring ice breakup and melting permafrost	Kobuk Valley NP	A1B	Durand et al. 2011
	Pinfish (*Lagodon rhomboides*) estuarine habitat decrease	Everglades NP	+1 °C, precipitation ±10%, sea level +46 cm	Kearney et al. 2015
	Yellowstone cutthroat trout (*Oncorhynchus clarkii bouvieri*) habitat decrease in low-elevation streams, but growth increase at higher elevations	Yellowstone NP	A2	Al-Chokhachy et al. 2013
Insect pests	Argentine ant (*Linepithema humile*) habitat increase with temperature increase	Haleakala NP	HS	Hartley, Krushelnycky, and Lester 2010
Insects	Karner Blue butterfly (*Lycaeides melissa samuelis*) susceptible to higher temperatures, among other factors	Indiana Dunes NL	HS	Grundel and Pavlovic 2007
	Meltwater stonefly (*Lednia tumana*) habitat reduction 80%	Glacier NP	A1B	Muhlfeld et al. 2011
Mammals	For 213 mammal species, average park loss of 8% of species, gain 48%, rodents 40% of the species influx	Acadia NP, Big Bend NP, Glacier NP, Great Smoky Mountains NP, Shenandoah NP, Yellowstone NP, Yosemite NP, Zion NP	CO_2 doubling	Burns, Johnston, and Schmitz 2003
	For 39 mammal species, habitat decline for 62%	Bering Land Bridge N. Pres., Cape Krusenstern NP, Gates of the Arctic NP Pres., Kobuk Valley NP, Noatak N. Pres.	A1B	Marcot et al. 2015
	American bison (*Bison bison*) forage quality and animal weight reduction from hotter and drier conditions	Western United States; Badlands NP, Great Sand Dunes NP Pres.	HS	Craine 2013

(*continued*)

Table 6.3 **(*continued*)**

Resource	Vulnerability	National park	Scenario	Reference
Mammals				
	American marten (*Martes americana*), American pika (*Ochotona princeps*), Canada lynx (*Lynx canadensis*), hoary marmot (*Marmota caligata*), mountain goat (*Oreamnos americanus*), and wolverine (*Gulo gulo*) range reductions	Washington; Mount Rainier NP, North Cascades NP, Olympic NP	A1B, A2	Johnston, Freund, and Schmitz 2012
	American pika (*Ochotona princeps*) extirpation	Lassen NP, Sequoia NP, Yosemite NP	RCP4.5, RCP8.5	Stewart et al. 2015
	Belding's ground squirrel (*Urocitellus beldingi*) habitat reduction 52%–99%	Lassen NP, Sequoia NP, Yosemite NP	A2	Morelli et al. 2012
	Desert bighorn sheep (*Ovis canadensis nelsoni*) habitat upslope shift	California; Joshua Tree NP, Mojave N. Pres.	HS	Epps et al. 2006; Epps et al. 2007
	Indiana bat (*Myotis sodalis*) northward range shift away from the park	Eastern United States; Cumberland Gap NHP	B2, A1B	Loeb and Winters 2013
	Northern elephant seals (*Mirounga angustirostris*) haul-out habitat inundation up to 69%	Point Reyes NS	Sea level +1.4 m	Funayama et al. 2013
	Polar bear (*Ursus maritimus*) threatened by loss of sea ice habitat	Polar areas; NPs	HS	US Department of the Interior 2008
	Wolverine (*Gulo gulo*) habitat northward shift	Western United States; Glacier NP	RCP2.6, RCP4.5, RCP8.5	Peacock 2011
	Wolverine (*Gulo gulo*) habitat reduction	Western United States; Glacier NP	A1B	McKelvey et al. 2011
Reptiles	American alligator (*Alligator mississippiensis*) habitat reduction under drier scenarios	Everglades NP	+1.5°C, precipitation ±10%, sea level +31 cm	Catano et al. 2015
	Desert tortoise (*Gopherus agassizii*) habitat reduction 57%–93%, common chuckwalla (*Sauromalus ater*) habitat reduction 49%–74%	Joshua Tree NP	+1°C–3°C, precipitation –25 to –75%	Barrows 2011

	Green turtles (*Chelonia mydas*) nest flooding from tropical storms	Canaveral NS	HS	Pike and Stiner 2007
	Lizards (*Sceloporus* spp.) habitat reduction by half	Joshua Tree NP	+1°C–3°C, precipitation −25 to −75%	Barrows and Fisher 2014
	Loggerhead sea turtle (*Caretta caretta*) hatching success reduction up to 15%	Buck Island Reef NM, Padre Island NS	B1, A1B, A2	Pike 2014
Cultural				
Archaeological mounds	Oyster shell middens flooding and erosion from sea-level rise	Canaveral NS	HS	Stalter and Kincaid 2004
Historical monuments	Flooding from sea-level rise and storm surge	Washington, DC; Constitution Gardens, Korean War Veterans Memorial, Martin Luther King Jr. Memorial, National Capital Parks, National Mall, Pennsylvania Avenue NHS, Theodore Roosevelt Island Park, Thomas Jefferson Memorial, World War I Memorial, World War II Memorial	Sea level +0.1–5 m	Ayyub, Braileanu, and Qureshi 2012
Historical monuments	Flooding from sea-level rise and storm surge	UNESCO World Heritage Sites globally; Independence NHP, San Juan NHS, Statue of Liberty NM	Sea level +2.8–4.4 m	Marzeion and Levermann 2014

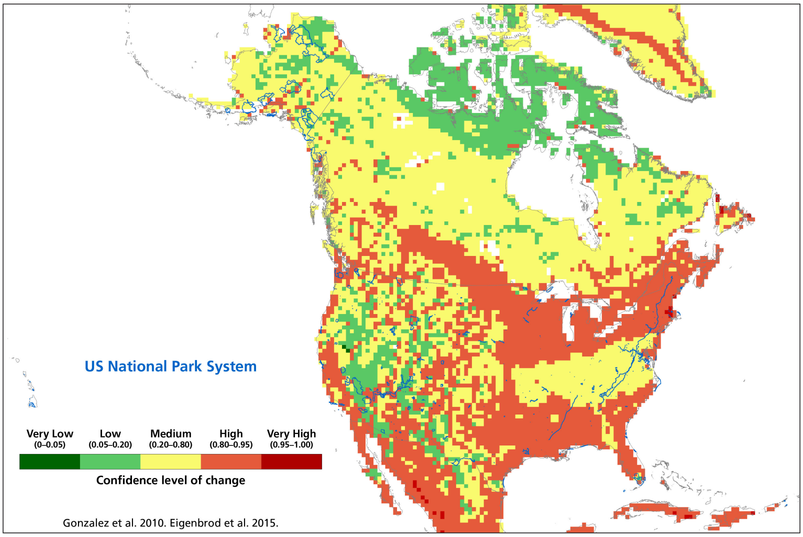
Note: Emissions scenarios and projections of global average temperature increase (mean ±standard deviation) from IPCC (2013): 1986–2005 to 2081–2100, RCP2.6 = 1°C ±0.4°C, RCP4.5 = 1.8°C ±0.5°C, RCP6.0 = 2.2°C ±0.5°C, RCP8.5 = 3.7°C ±0.7°C; IPCC (2007b): 1980–1999 to 2090–2099, B1 = 1.8°C (1.1°C–2.9°C), B2 = 2.4°C (1.4°C–3.8°C), A1B = 2.8°C (1.7°C–4.4°C), A2 = 3.4°C (2.0°C–5.4°C), A1FI = 4.0°C (2.4°C–6.4°C); IPCC (2001b): CO_2 doubling in 70 years = 3.5°C ±0.9°C. HS = sensitivity based on historical or experimental data. See table 6.1 abbreviations.

Areas of high vulnerability include parts of Acadia, Joshua Tree, Mount Rainier, Rocky Mountain, Saguaro, and Yosemite National Parks, while potential refugia include parts of Death Valley National Park, Organ Pipe Cactus National Monument, and White Sands National Monument.

Bandelier National Monument and the southwestern United States are vulnerable to tree dieback and possible conversion of some forest to grassland because of drought stress under climate change rising to its highest level in 1,000 years (Williams et al. 2013). Everglades National Park is vulnerable to inundation of extensive areas because of sea-level rise and alterations of upland vegetation due to changes in precipitation (see table 6.3). Joshua Tree National Park is vulnerable to nearly complete disappearance of suitable habitat for the Joshua tree (*Yucca brevifolia*) (Cole et al. 2011; Barrows and Murphy-Mariscal 2012).

Warmer and wetter conditions render many ecosystems vulnerable to increased spread of invasive species (Bellard et al. 2013). The Appalachian Trail is vulnerable to increased spread of the invasive tree-of-heaven (*Ailanthus altissima*) (Clark, Wang, and August 2014).

Although wildfire is a natural and necessary part of many forest ecosystems, climate change could increase fire frequencies far above levels to



6.3. Vulnerability of ecosystems to combined effects of biome shifts due to climate change and habitat fragmentation due to land-cover change, based on 1901–2002 climate trends, 1990–2100 vegetation projections, and 2009 land cover (Gonzalez et al. 2010; Eigenbrod et al. 2015).

which current vegetation are adapted (Turner et al., this volume, ch. 5). Under high emissions, hotter temperatures could increase wildfire frequencies in Yellowstone and Grand Teton National Parks and across the Greater Yellowstone Ecosystem by 300% to 1,000% by 2100 (Westerling et al. 2011).

Vulnerability of Animals

Analyses project potential future vulnerabilities to climate change of corals, insects, amphibians, reptiles, birds, and mammals in many national parks (see table 6.3). Climate change renders coral reefs vulnerable to bleaching from warmer waters and to dissolving from ocean acidification (Wong et al. 2014). Corals in the National Park of American Samoa show some tolerance and adaptive capacity (Craig, Birkeland, and Belliveau 2001; Oliver and Palumbi 2009; Palumbi et al. 2014). In Dry Tortugas National Park, ocean acidification could especially affect early life-phases of coral (Kuffner, Hickey, and Morrison 2013).

Numerous wildlife species in US national parks that are listed as endangered under the US Endangered Species Act are vulnerable to increased mortality under climate change. In Indiana Dunes National Lakeshore, the Karner blue butterfly (*Lycaeides melissa samuelis*) is vulnerable to extirpation under hotter temperatures because of acceleration of larval development, decreased fitness, and a lack of wild lupines (*Lupinus perennis*), its food source (Grundel and Pavlovic 2007). The Devil's Hole pupfish (*Cyprinodon diabolis*), found in the world in only one small pool in Death Valley National Park, is vulnerable to a reduction of favorable spawning conditions from 74 days to 57 days under high emissions (Hausner et al. 2014). At Canaveral National Seashore, green turtles (*Chelonia mydas*) are vulnerable to potential flooding of nests from increases in storms (Pike and Stiner 2007). Using data from national parks and other areas, the US government has added two species to the US Endangered Species Act lists because of vulnerability to climate change. The polar bear (*Ursus maritimus*) is listed as endangered under the act because of the reduction of its sea ice habitat under climate change (US Department of the Interior 2008). 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 act because of urban development, sea-level rise, and reductions in food species due to climate change (US Department of the Interior 2014).

Upslope and poleward shifting of cooler climates and biomes increases the vulnerability of high-elevation mammals. American pika (*Ochotona princeps*) is vulnerable to extirpation in Lassen, Sequoia, and Yosemite National Parks (Stewart et al. 2015). American pika, Canada lynx (*Lynx canadensis*), hoary marmot (*Marmota caligata*), and the wolverine (*Gulo gulo*) are vulnerable to range contractions in Mount Rainier, North Cascades, and Olympic National Parks (Johnston, Freund, and Schmitz 2012).

Vulnerability of Cultural Resources

Thawing and exposure of archaeological artifacts as glaciers melt in Wrangell–Saint Elias and Lake Clark National Parks and Preserves can cause organic objects to decompose and be lost forever (Dixon, Manley, and Lee 2005; VanderHoek et al. 2012) if they are not detected, secured, and protected. In addition, sea-level rise renders vulnerable cultural sites in national parks along the Atlantic and Pacific coasts, including oyster shell middens over a millennium old in Canaveral National Seashore (Stalter and Kincaid 2004), the National Mall and other monuments in Washington, DC (Ayyub, Braileanu, and Qureshi 2012), and UNESCO World Heritage Sites such as the Statue of Liberty National Monument (Marzeion and Levermann 2014).

Conclusions

Field evidence documents impacts of human climate change across the US National Park System. The alteration of ecosystems and physical and cultural resources in US national parks reflects the widespread impact of climate change around the world. If we do not reduce greenhouse gas emissions, vulnerability analyses project future damage to the irreplaceable and globally unique wonders of US national parks.

While dedicated park managers may make extraordinary efforts to protect the national parks, the most effective way to attack a problem is to eliminate its cause. Reducing greenhouse gas emissions will reduce the magnitude of future climate change and threats to national parks. Climate change projections are not predictions—they are not inevitable. Greenhouse gas mitigation analyses by the IPCC (2014b) show that it is within our power to avoid the most drastic impacts of climate change by improving energy efficiency, installing renewable energy systems, conserving forests with large carbon stocks, expanding public transit, and using other measures to reduce emissions. Billions of small actions caused the problem of climate change, so billions of small sustainable actions can help us solve it.

Literature Cited

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.

Albright, W. L., and D. L. Peterson. 2013. Tree growth and climate in the Pacific Northwest, North America: a broad-scale analysis of changing growth environments. Journal of Biogeography **40**:2119–2133.

Al-Chokhachy, R., J. Alder, S. Hostetler, R. Gresswell, and B. Shepard. 2013. Thermal controls of Yellowstone cutthroat trout and invasive fishes under climate change. Global Change Biology **19**:3069–3081.

Allen, C. D., and D. D. Breshears. 1998. Drought-induced shift of a forest–woodland ecotone: rapid landscape response to climate variation. Proceedings of the National Academy of Sciences USA **95**:14839–14842.

Arendt, A. A., S. B. Luthcke, C. F. Larsen, W. Abdalati, W. B. Krabill, and M. J. Beedle. 2008. Validation of high-resolution GRACE mascon estimates of glacier mass changes in the St Elias Mountains, Alaska, USA, using aircraft laser altimetry. Journal of Glaciology 54:778–787.

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

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.

Balling, R. C., G. A. Meyer, and S. G. Wells. 1992. Climate change in Yellowstone National Park—is the drought-related risk of wildfires increasing? Climatic Change **22**:35–45.

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.

Barnett, T. P., and D. W. Pierce. 2008. When will Lake Mead go dry? Water Resources Research **44**:W03201.

Barnett, T. P., D. W. Pierce, H. G. Hidalgo, C. Bonfils, B. D. Santer, T. Das, G. Bala, et al. 2008. Human-induced changes in the hydrology of the western United States. Science **319**:1080–1083.

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.

Barrows, C. W. 2011. Sensitivity to climate change for two reptiles at the Mojave-Sonoran Desert interface. Journal of Arid Environments **75**:629–635.

Barrows, C. W., and M. Fisher. 2014. Past, present and future distributions of a local assemblage of congeneric lizards in southern California. Biological Conservation **180**:97–107.

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.

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.

Bearup, L. A., R. M. Maxwell, D. W. Clow, J. E. McCray. 2014. Hydrological effects of forest transpiration loss in bark beetle-impacted watersheds. Nature Climate Change **4**:481–486.

Bellard, C., W. Thuiller, B. Leroy, P. Genovesi, M. Bakkenes, and F. Courchamp. 2013. Will climate change promote future invasions? Global Change Biology **19**:3740–3748.

Bindoff, N. L., P. A. Stott, K. M. AchutaRao, M. R. Allen, N. Gillett, D. Gutzler, K. Hansingo, et al. 2013. Detection and attribution of climate change: from global to regional. Pages 867–952 *in* T. F. Stocker, D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, et al., eds. Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom, and New York, New York.

Bonfils, C., B. D. Santer, D. W. Pierce, H. G. Hidalgo, G. Bala, T. Das, T. P. Barnett, et al. 2008. Detection and attribution of temperature changes in the mountainous western United States. Journal of Climate **21**:6404–6424.

Breshears, D. D., N. S. Cobb, P. M. Rich, K. P. Price, C. D. Allen, R. G. Balice, W. H. Romme, et al. 2005. Regional vegetation die-off in response to global-change-type drought. Proceedings of the National Academy of Sciences USA **102**:15144–15148.

Brodie, J., E. Post, F. Watson, and J. Berger. 2012. Climate change intensification of herbivore impacts on tree recruitment. Proceedings of the Royal Society B **279**:1366–1370.

Brown, J., J. Harper, and N. Humphrey. 2010. Cirque glacier sensitivity to 21st century warming: Sperry Glacier, Rocky Mountains, USA. Global and Planetary Change **74**: 91–98.

Bunn, A. G, L. J. Graumlich, and D. L. Urban. 2005. Trends in twentieth-century tree growth at high elevations in the Sierra Nevada and White Mountains, USA. The Holocene **15**:481–488.

Burns, C. E., K. M. Johnston, and O. J. Schmitz. 2003. Global climate change and mammalian species diversity in US national parks. Proceedings of the National Academy of Sciences USA **100**:11474–11477.

Carbone, M. S., A. P. Williams, A. R. Ambrose, C. M. Boot, E. S. Bradley, T. E. Dawson, S. M. Schaeffer, J. P. Schimel, and C. J. Still. 2013. Cloud shading and fog drip influence the metabolism of a coastal pine ecosystem. Global Change Biology **19**:484–497.

Caruso, N. M., M. W. Sears, D. C. Adams, and K. R. Lips. 2014. Widespread rapid reductions in body size of adult salamanders in response to climate change. Global Change Biology **20**:1751–1759.

Catano, C. P., S. S. Romañach, J. M. Beerens, L. G. Pearlstine, L. A. Brandt, K. M. Hart, F. J. Mazzotti, and J. C. Trexler. 2015. Using scenario planning to evaluate the impacts of climate change on wildlife populations and communities in the Florida Everglades. Environmental Management **55**:807–823.

Cavanaugh, K. C., J. R. Kellner, A. J. Forde, D. S. Gruner, J. D. Parker, W. Rodriguez, and I. C. Feller. 2014. Poleward expansion of mangroves is a threshold response to decreased frequency of extreme cold events. Proceedings of the National Academy of Sciences USA **111**:723–727.

Chang, T., A. J. Hansen, and N. Piekielek. 2014. Patterns and variability of projected bioclimatic habitat for *Pinus albicaulis* in the greater Yellowstone area. PLoS ONE **9**:e111669.

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.

Church, J. A., P. U. Clark, A. Cazenave, J. M. Gregory, S. Jevrejeva, A. Levermann, M. A.

Merrifield, et al. 2013. Sea level change. Pages 1137–1216 *in* T. F. Stocker, D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, et al., eds. Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom, and New York, New York.

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

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 B **369**:20130192.

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.

Craig, P., C. Birkeland, and S. Belliveau. 2001. High temperatures tolerated by a diverse assemblage of shallow-water corals in American Samoa. Coral Reefs **20**:185–189.

Craine, J. M. 2013. Long-term climate sensitivity of grazer performance: a cross-site study. PLoS ONE **8**:e67065.

Crossman, J., M. N. Futter, P. G. Whitehead. 2013. The significance of shifts in precipitation patterns: modelling the impacts of climate change and glacier retreat on extreme flood events in Denali National Park, Alaska. PLoS ONE **8**:e74054.

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

Damschen, E. I., S. Harrison, and J. B. Grace. 2010. Climate change effects on an endemic-rich edaphic flora: resurveying Robert H. Whittaker's Siskiyou sites (Oregon, USA). Ecology **91**:3609–3619.

Dawadi, S., and S. Ahmad. 2012. Changing climatic conditions in the Colorado River Basin: implications for water resources management. Journal of Hydrology **430–431**: 127–141.

DeFalco, L. A., T. C. Esque, S. J. Scoles-Sciulla, and J. Rodgers. 2010 Desert wildfire and severe drought diminish survivorship of the long-lived Joshua tree (*Yucca brevifolia*; Agavaceae). American Journal of Botany **97**:243–250.

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.

Dolanc, C. R., J. H. Thorne, and H. D. Safford. 2013. Widespread shifts in the demographic structure of subalpine forests in the Sierra Nevada, California, 1934 to 2007. Global Ecology and Biogeography **22**:264–276.

Driscoll, W. W., G. C. Wiles, R. D. D'Arrigo, and M. Wilmking. 2005. Divergent tree growth response to recent climatic warming, Lake Clark National Park and Preserve, Alaska. Geophysical Research Letters **32**:L20703.

Durand, J. R., R. A. Lusardi, D. M. Nover, R. J. Suddeth, G. Carmona-Catot, C. R. Connell-Buck, S. E. Gatzke, et al. 2011. Environmental heterogeneity and community structure of the Kobuk River, Alaska, in response to climate change. Ecosphere **2**:art44.

Eakin, C. M., J. A. Morgan, S. F. Heron, T. B. Smith, G. Liu, L. Alvarez-Filip, B. Baca, et al. 2010. Caribbean corals in crisis: record thermal stress, bleaching, and mortality in 2005. PLoS ONE **5**:e13969.

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

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

Ellis, R. A., D. J. Jacob, M. P. Sulprizio, L. Zhang, C. D. Holmes, B. A. Schichtel, T. Blett, et al. 2013. Present and future nitrogen deposition to national parks in the United States: critical load exceedances. Atmospheric Chemistry and Physics **13**:9083–9095.

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.

Epps, C. W., J. D. Wehausen, V. C. Bleich, S. G. Torres, and J. S. Brashares. 2007. Optimizing dispersal and corridor models using landscape genetics. Journal of Applied Ecology **44**:714–724.

Fischer, D. T., C. J. Still, and A. P. Williams. 2009. Significance of summer fog and overcast for drought stress and ecological functioning of coastal California endemic plant species. Journal of Biogeography **36**:783–799.

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.

Foti, R., M. del Jesus, A. Rinaldo, and I. Rodriguez-Iturbe. 2013. Signs of critical transition in the Everglades wetlands in response to climate and anthropogenic changes. Proceedings of the National Academy of Sciences USA **110**:6296–6300.

Franklin, J. F., W. H. Moir, G. W. Douglas, and C. Wiberg. 1971. Invasion of subalpine meadows by trees in the Cascade Range, Washington and Oregon. Arctic and Alpine Research **3**:215–224.

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.

Gahl, M. K., and A. J. K. Calhoun. 2010. The role of multiple stressors in ranavirus-caused amphibian mortalities in Acadia National Park wetlands. Canadian Journal of Zoology **88**:108–121.

Garrity, S. R., C. D. Allen, S. P. Brumby, C. Gangodagamage, N. G. McDowell, D. M. Cai. 2013. Quantifying tree mortality in a mixed species woodland using multitemporal high spatial resolution satellite imagery. Remote Sensing of Environment **129**:54–65.

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

Gonzalez, P. 2011. Science for natural resource management under climate change. Issues in Science and Technology **27**(4):65–74.

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.

Granshaw, F. D., and A. G. Fountain. 2006. Glacier change (1958–1998) in the North Cascades National Park Complex, Washington, USA. Journal of Glaciology **52**:251–256.

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.

Hall, M. H. P., and D. B. Fagre. 2003. Modeled climate-induced glacier change in Glacier National Park, 1850–2100. BioScience **53**:131–140.

Hameed, S. O., K. A. Holzer, A. N. Doerr, J. H. Baty, and M. W. Schwartz. 2013. The value of a multi-faceted climate change vulnerability assessment to managing protected lands: lessons from a case study in Point Reyes National Seashore. Journal of Environmental Management **121**:37–47.

Hansen, A. J., N. Piekielek, C. Davis, J. Haas, D. M. Theobald, J. E. Gross, W. B. Monahan, T. Olliff, and S. W. Running. 2014. Exposure of US national parks to land use and climate change 1900–2100. Ecological Applications **24**:484–502.

Hartley, S., P. D. Krushelnycky, and P. J. Lester. 2010. Integrating physiology, population dynamics and climate to make multi-scale predictions for the spread of an invasive insect: the Argentine ant at Haleakala National Park, Hawaii. Ecography **33**:83–94.

Hausner, M. B., K. P. Wilson, D. B. Gaines, F. Suárez, G. G. Scoppettone, and S. W. Tyler. 2014. Life in a fishbowl: prospects for the endangered Devils Hole pupfish (*Cyprinodon diabolis*) in a changing climate. Water Resources Research **50**:7020–7034.

Hessl, A. E., and W. L. Baker. 1997. Spruce and fir regeneration and climate in the forest-tundra ecotone of Rocky Mountain National Park, Colorado, USA. Arctic and Alpine Research **29**:173–183.

Hitch, A. T., and P. L. Leberg. 2007. Breeding distributions of North American bird species moving north as a result of climate change. Conservation Biology **21**:534–539.

Hoffman, M. J., A. G. Fountain, and J. M. Achuff. 2007. 20th-century variations in area of cirque glaciers and glacierets, Rocky Mountain National Park, Rocky Mountains, Colorado, USA. Annals of Glaciology **46**:349–354.

Intergovernmental Panel on Climate Change (IPCC). 2001a. Climate change 2001: impacts, adaptation, and vulnerability. Cambridge University Press, Cambridge, United Kingdom.

———. 2001b. Climate change 2001: the scientific basis. Cambridge University Press, Cambridge, United Kingdom.

———. 2007a. Climate change 2007: impacts, adaptation, and vulnerability. Cambridge University Press, Cambridge, United Kingdom.

———. 2007b. Climate change 2007: the physical science basis. Cambridge University Press, Cambridge, United Kingdom.

———. 2012. Managing the risks of extreme events and disasters to advance climate change adaptation. Cambridge University Press, Cambridge, United Kingdom.

———. 2013. Climate change 2013: the physical science basis. Cambridge University Press, Cambridge, United Kingdom.

———. 2014a. Climate change 2014: impacts, adaptation, and vulnerability. Cambridge University Press, Cambridge, United Kingdom.

———. 2014b. Climate change 2014: mitigation of climate change. Cambridge University Press, Cambridge, United Kingdom.

Jakubos, B., and W. H. Romme. 1993. Invasion of subalpine meadows by lodgepole pine in Yellowstone National Park, Wyoming, USA. Arctic and Alpine Research **25**: 382–390.

Janke, J. R. 2005. Modeling past and future alpine permafrost distribution in the Colorado Front Range. Earth Surface Processes and Landforms **30**:1495–1508.

Johnston, K. M., K. A. Freund, and O. J. Schmitz. 2012. Projected range shifting by montane mammals under climate change: implications for Cascadia's national parks. Ecosphere **3**:art97.

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.

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.

Kasischke, E. S., D. L. Verbyla, T. S. Rupp, A. D. McGuire, K. A. Murphy, R. Jandt, J. L. Barnes, et al. 2010. Alaska's changing fire regime—implications for the vulnerability of its boreal forests. Canadian Journal of Forest Research **40**:1313–1324.

Kearney, K. A., M. Butler, R. Glazer, C. R. Kelble, J. E. Serafy, and E. Stabenau. 2015. Quantifying Florida Bay habitat suitability for fishes and invertebrates under climate change scenarios. Environmental Management **55**:836–856.

Klasner, F. L., and D. B. Fagre. 2002. A half century of change in alpine treeline patterns at Glacier National Park, Montana, USA. Arctic, Antarctic, and Alpine Research **34**:49–56.

Koch, M. S., C. Coronado, M. W. Miller, D. T. Rudnick, E. Stabenau, R. B. Halley, and F. H. Sklar. 2015. Climate change projected effects on coastal foundation communities of the greater Everglades using a 2060 scenario: need for a new management paradigm. Environmental Management **55**:857–875.

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.

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.

Kuffner, I. B., B. H. Lidz, J. H. Hudson, and J. S. Anderson. 2015. A century of ocean warming on Florida Keys coral reefs: historic in situ observations. Estuaries and Coasts **38**:1085–1096.

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.

Larson, R. P., J. M. Byrne, D. L. Johnson, S. W. Kienzie, and M. G. Letts. 2011. Modelling climate change impacts on spring runoff for the Rocky Mountains of Montana and Alberta II: runoff change projections using future scenarios. Canadian Water Resources Journal **36**:35–52.

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

Lesica, P. 2014. Arctic-alpine plants decline over two decades in Glacier National Park, Montana, USA. Arctic, Antarctic, and Alpine Research **46**:327–332.

Lesica, P., and B. McCune. 2004. Decline of arctic-alpine plants at the southern margin of their range following a decade of climatic warming. Journal of Vegetation Science **15**:679–690.

Levine, J. M., A. K. McEachern, and C. Cowan. 2008. Rainfall effects on rare annual plants. Journal of Ecology **96**:795–806.

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

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

Logan, J. A., W. W. Macfarlane, and L. Willcox. 2010. Whitebark pine vulnerability to climate-driven mountain pine beetle disturbance in the Greater Yellowstone Ecosystem. Ecological Applications **20**:895–902.

Loope, L. L., and T. W. Giambelluca. 1998. Vulnerability of island tropical montane cloud forests to climate change, with special reference to East Maui, Hawaii. Climatic Change **39**:503–517.

Lucas, K. L., and G. A. Carter. 2010. Decadal changes in habitat-type coverage on Horn Island, Mississippi, USA. Journal of Coastal Research **26**:1142–1148.

Lutz, J. A., J. W. van Wagtendonk, and J. F. Franklin. 2010. Climatic water deficit, tree species ranges, and climate change in Yosemite National Park. Journal of Biogeography **37**:936–950.

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.

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.

Marlon, J. R., P. J. Bartlein, D. G. Gavin, C. J. Long, R. S. Anderson, C. E. Briles, K. J. Brown, et al. 2012. Long-term perspective on wildfires in the western USA. Proceedings of the National Academy of Sciences USA **109**:E535–E543.

Marzeion, B., J. G. Cogley, K. Richter, and D. Parkes. 2014. Attribution of global glacier mass loss to anthropogenic and natural causes. Science **345**:919–921.

Marzeion, B., and A. Levermann. 2014. Loss of cultural world heritage and currently inhabited places to sea-level rise. Environmental Research Letters **9**:034001.

McEachern, A. K., D. M. Thomson, and K. A. Chess. 2009. Climate alters response of an endemic island plant to removal of invasive herbivores. Ecological Applications **19**:1574–1584.

McIntyre, P. J., J. H. Thorne, C. R. Dolanc, A. L. Flint, L. E. Flint, M. Kelly, and D. D. Ackerly. 2015. Twentieth-century shifts in forest structure in California: denser forests, smaller trees, and increased dominance of oaks. Proceedings of the National Academy of Sciences USA **112**:1458–1463.

McKelvey, K. S., J. P. Copeland, M. K. Schwartz, J. S. Littell, K. B. Aubry, J. R. Squires, S. A. Parks, M. M. Elsner, and G. S. Mauger. 2011. Climate change predicted to shift wolverine distributions, connectivity, and dispersal corridors. Ecological Applications **21**: 2882–2897.

McMenamin, S. K., E. A. Hadly, and C. K. Wright. 2008. Climatic change and wetland desiccation cause amphibian decline in Yellowstone National Park. Proceedings of the National Academy of Sciences USA **105**:16988–16993.

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.

Monahan, W. B., T. Cook, F. Melton, J. Connor, and B. Bobowski. 2013. Forecasting distributional responses of limber pine to climate change at management-relevant scales in Rocky Mountain National Park. PLoS ONE **8**:e83163.

Monahan, W. B., and N. A. Fisichelli. 2014. Climate exposure of US national parks in a new era of change. PLoS ONE **9**:e101302.

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

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.

Moss, R. H., J. A. Edmonds, K. A. Hibbard, M. R. Manning, S. K. Rose, D. P. van Vuuren, T. R. Carter, et al. 2010. The next generation of scenarios for climate change research and assessment. Nature **463**:747–756.

Muhlfeld, C. C., J. J. Giersch, F. R. Hauer, G. T. Pederson, G. Luikart, D. P. Peterson, C. C. Downs, and D. B. Fagre. 2011. Climate change links fate of glaciers and an endemic alpine invertebrate. Climatic Change **106**:337–345.

Muller, E. M., C. S. Rogers, A. S. Spitzack, and R. van Woesik. 2008. Bleaching increases likelihood of disease on Acropora palmata (Lamarck) in Hawksnest Bay, St John, US Virgin Islands. Coral Reefs 27:191–195.

Munson, S. M., J. Belnap, and G. S. Okin. 2011. Responses of wind erosion to climate-induced vegetation changes on the Colorado Plateau. Proceedings of the National Academy of Sciences USA **108**:3854–3859.

Munson, S. M., J. Belnap, C. D. Schelz, M. Moran, and T. W. Carolin. 2011. On the brink of change: plant responses to climate on the Colorado Plateau. Ecosphere **2**:art68.

Munson, S. M., R. H. Webb, J. Belnap, J. A. Hubbard, D. E. Swann, and S. Rutman. 2012. Forecasting climate change impacts to plant community composition in the Sonoran Desert region. Global Change Biology **18**:1083–1095.

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.

Necsoiu, M., C. L 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.

Nungesser, M., C. Saunders, C. Coronado-Molina, J. Obeysekera, J. Johnson, C. McVoy, and B. Benscoter. 2015. Potential effects of climate change on Florida's Everglades. Environmental Management **55**:824–835.

Oliver, T. A., and S. R. Palumbi. 2009. Distributions of stress-resistant coral symbionts match environmental patterns at local but not regional scales. Marine Ecology Progress Series **378**:93–103.

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.

Peacock, S. 2011. Projected 21st century climate change for wolverine habitats within the contiguous United States. Environmental Research Letters **6**:014007.

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.

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.

Pelto, M. S. 2006. The current disequilibrium of North Cascade glaciers. Hydrological Processes **20**:769–779.

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.

Pierce, D. W., T. P., Barnett, H. G. Hidalgo. T. Das, C. Bonfils, B. D. Santer, G. Bala, et al. 2008. Attribution of declining western US snowpack to human effects. Journal of Climate **21**:6425–6444.

Pike, D. A. 2014. Forecasting the viability of sea turtle eggs in a warming world. Global Change Biology **20**:7–15.

Pike, D. A., R. L. Antworth, and J. C. Stiner. 2006. Earlier nesting contributes to shorter nesting seasons for the Loggerhead Seaturtle, *Caretta caretta*. Journal of Herpetology **40**:91–94.

Pike, D. A., and J. C. Stiner. 2007. Sea turtle species vary in their susceptibility to tropical cyclones. Oecologia **153**:471–478.

Portmann, R. W., S. Solomon, and G. C. Hegerl. 2009. Spatial and seasonal patterns in climate change, temperatures, and precipitation across the United States. Proceedings of the National Academy of Sciences USA **106**:7324–7329.

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.

Rehfeldt, G. E., D. E. Ferguson, and N. L. Crookston. 2009. Aspen, climate, and sudden decline in western USA. Forest Ecology and Management **258**:2353–2364.

Rhein, M., S. R. Rintoul, S. Aoki, E. Campos, D. Chambers, R. A. Feely, S. Gulev, et al. 2013. Observations: ocean. Pages 255–316 *in* T. F. Stocker, D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, et al., eds. Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom, and New York, New York.

Riordan, B., D. Verbyla, and A. D. McGuire. 2006. Shrinking ponds in subarctic Alaska based on 1950–2002 remotely sensed images. Journal of Geophysical Research **111**:G04002.

Rochefort, R. M., and D. L. Peterson. 1996. Temporal and spatial distribution of trees in subalpine meadows of Mount Rainier National Park, Washington, USA. Arctic and Alpine Research **28**:52–59.

Roush, W., J. S. Munroe, and D. B. Fagre. 2007. Development of a spatial analysis method using ground based repeat photography to detect changes in the alpine treeline ecotone, Glacier National Park, Montana, USA. Arctic, Alpine, and Antarctic Research **39**:297–308.

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

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.

———. 2001. Modeling the influence of topographic barriers on treeline advance at the forest-tundra ecotone in northwestern Alaska. Climatic Change **48**:399–416.

Ryan, M. E., W. J. Palen, M. J. Adams, and R. M. Rochefort. 2014. Amphibians in the climate vise: loss and restoration of resilience of montane wetland ecosystems in the western US. Frontiers in Ecology and the Environment **12**:232–240.

Saha, A. K., S. Saha, J. Sadle, J. Jiang, M. S. Ross, R. M. Price, L. S. L. O. Sternberg, and K. S. Wendelberger. 2011. Sea level rise and South Florida coastal forests. Climatic Change **107**:81–108.

Settele, J., R. Scholes, R. Betts, S. Bunn, P. Leadley, D. Nepstad, J. T. Overpeck, and M. A. Taboada. 2014. Terrestrial and inland water systems. Pages 217–360 *in* C. B. Field,

V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, et al., eds. Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom, and New York, New York.

Smith, J. R., P. Fong, and R. F. Ambrose. 2006. Dramatic declines in mussel bed community diversity: response to climate change? Ecology **87**:1153–1161.

Stalter, R., and D. Kincaid. 2004. The vascular flora of five Florida shell middens. Journal of the Torrey Botanical Society **131**:93–103.

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.

Suarez, F., D. Binkley, M. W. Kaye, and R. Stottlemyer. 1999. Expansion of forest stands into tundra in the Noatak National Preserve, northwest Alaska. Ecoscience **6**:465–470.

Swetnam, T. W. 1993. Fire history and climate change in giant sequoia groves. Science 262:885–889.

Swetnam, T. W., C. H. Baisan, A. C. Caprio, P. M. Brown, R. Touchan, R. S. Anderson, and D. J. Hallett. 2009. Multi-millennial fire history of the Giant Forest, Sequoia National Park, California, USA. Fire Ecology **5**:120–150.

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

Taylor, A. H., and A. E. Scholl. 2012. Climatic and human influences on fire regimes in mixed conifer forests in Yosemite National Park, USA. Forest Ecology and Management **267**:144–156.

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

Tingley, M. W., W. B. Monahan, S. R. Beissinger, and C. Moritz. 2009. Birds track their Grinnellian niche through a century of climate change. Proceedings of the National Academy of Sciences USA **106**:19637–19643.

Todd, M. J., R. Muneepeerakul, F. Miralles-Wilhelm, A. Rinaldo, and I. Rodriguez-Iturbe. 2012. Possible climate change impacts on the hydrological and vegetative character of Everglades National Park, Florida. Ecohydrology **5**:326–336.

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

US Bureau of Reclamation. 2012. Colorado River Basin Water Supply and Demand Study. US Bureau of Reclamation, Washington, DC.

———. 2013. Lower Rio Grande Basin Study. US Bureau of Reclamation, Denver, Colorado.

US 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**:28212–28303.

———. 2014. Endangered and threatened wildlife and plants; threatened species status for the rufa red knot. Federal Register **79**:73706–73748.

VanderHoek, R., E. J. Dixon, N. L. Jarman, and R. M. Tedor. 2012. Ice patch archaeology in Alaska: 2000–10. Arctic **65**(S1):153–164.

van der Valk, A. G., J. C. Volin, and P. R. Wetzel. 2015. Predicted changes in interannual water-level fluctuations due to climate change and its implications for the vegetation of the Florida Everglades. Environmental Management **55**:799–806.

van Mantgem, P. J., N. L. Stephenson, J. C. Byrne, L. D. Daniels, J. F. Franklin, P. Z. Fule, M. E. Harmon, et al. 2009. Widespread increase of tree mortality rates in the western United States. Science **323**:521–524.

Vano, J. A., B. Udall, D. R. Cayan, J. T. Overpeck, L. D. Brekke, T. Das, H. C. Hartmann, et al. 2014. Understanding uncertainties in future Colorado River streamflow. Bulletin of the American Meteorological Society **95**:59–78.

Vaughan, D. G., J. C. Comiso, I. Allison, J. Carrasco, G. Kaser, R. Kwok, P. Mote, et al. 2013. Observations: cryosphere. Pages 317–382 *in* T. F. Stocker, D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, et al., eds. Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom, and New York, New York.

von Storch, H., and F. W. Zwiers. 1999. Statistical Analysis in Climate Research. Cambridge University Press, Cambridge, United Kingdom.

Wang, G. M., N. T. Hobbs, K. M. Giesen, H. Galbraith, D. S. Ojima, and C. E. Braun. 2002. Relationships between climate and population dynamics of white-tailed ptarmigan Lagopus leucurus in Rocky Mountain National Park, Colorado, USA. Climate Research **23**:81–87.

Westerling, A., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. Warming and earlier Spring increase western US forest wildfire activity. Science **313**:940–943.

Westerling, A. L., M. G. Turner, E. A. H. Smithwick, W. H. Romme, and M. G. Ryan. 2011. Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. Proceedings of the National Academy of Sciences USA **108**:13165–13170.

White, J. D., K. J. Gutzwiller, W. C. Barrow, L. Johnson-Randall, L. Zygo, and P. Swint. 2011. Understanding interaction effects of climate change and fire management on bird distributions through combined process and habitat models. Conservation Biology **25**:536–546.

Whittaker, R. H. 1960. Vegetation of the Siskiyou Mountains, Oregon and California. Ecological Monographs **30**:279–338.

Williams, A. P., C. D. Allen, A. K. Macalady, D. Griffin, C. A. Woodhouse, D. M. Meko, T. W. Swetnam, et al. 2013. Temperature as a potent driver of regional forest drought stress and tree mortality. Nature Climate Change **3**:292–297.

Williams, A. P., C. J. Still, D. T. Fischer, and S. W. Leavitt. 2008. The influence of summertime fog and overcast clouds on the growth of a coastal Californian pine: a tree-ring study. Oecologia **156**:601–611.

Womble, J. N., G. W. Pendleton, E. A. Mathews, G. M. Blundell, N. M. Bool, and S. M. Gende. 2010. Harbor seal (*Phoca vitulina richardii*) decline continues in the rapidly changing landscape of Glacier Bay National Park, Alaska 1992–2008. Marine Mammal Science **26**:686–697.

Wong, P. P., I. J. Losada, J. P. Gattuso, J. Hinkel, A. Khattabi, K. L. McInnes, Y. Saito, and A. Sallenger. 2014. Coastal systems and low-lying areas. Pages 361–410 *in* C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, et al., eds. Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom, and New York, New York.

Woodward, A., E. G. Schreiner, and D. G. Silsbee. 1995. Climate, geography, and tree establishment in subalpine meadows of the Olympic Mountains, Washington, USA. Arctic and Alpine Research **27**:217–225.
Zolbrod, N., and D. L. Peterson. 1999. Response of high-elevation forests in the Olympic Mountains to climatic change. Canadian Journal of Forest Research **29**:1966–1978.

Patrick Gonzalez, Ph.D.
U.S. National Park Service, Principal Climate Change Scientist
University of California, Berkeley, Associate Adjunct Professor

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