State of Science

Climate change impacts and carbon in U.S. national parks

By Patrick Gonzalez

Abstract

New spatial analyses of climate data and 123 peer-reviewed scientific publications document impacts of climate change and carbon stocks and emissions in the U.S. National Park System. Ninety-six percent of land administered by the National Park Service (NPS) is located in areas of observed warming in the 20th century, with an average mean annual temperature increase of 0.6 ± 0.5°C (1.1 ± 0.9°F). Scientific evidence attributes this warming to human greenhouse gas emissions. Field measurements in national parks have detected glacial melt, decreased snowfall and snowpack, earlier spring warmth and streamflow, sea-level rise, increased conifer mortality, and shifts of vegetation biomes, small-mammal ranges, and winter bird ranges. Analyses attribute these impacts to climate change. In California, the National Park Service manages ecosystems with some of the highest forest carbon densities in the world. Carbon emissions from fossil fuel use in parks that cover 10% of system area are equivalent to the emissions of a U.S. city of 21,000 people. These published scientific results provide national parks with information for vulnerability analyses of key resources, adaptation of resource management, and the reduction of climate change through forest conservation and management and energy conservation and efficiency.

Key words: attribution, carbon, detection, impacts, vulnerability

EMISSIONS FROM HUMAN ACTIVITIES have increased atmospheric concentrations of greenhouse gases, causing an increase in global average surface temperature of 0.7 ± 0.2°C (1.3 ± 0.4°F) from 1906 to 2005 (IPCC 2007a) and other changes in climate. Field measurements from around the world show that climate change is fundamentally altering ecosystems by shifting biomes (major vegetation formations; Gonzalez et al. 2010), leading to the extinction of amphibian species (Pounds et al. 2006), and causing numerous other changes (IPCC 2007b). This article presents a new synthesis of published scientific research on climate change documented in the National Park System and provides information for vulnerability analyses, adaptation measures, and carbon management.

Analyses of climate change in national parks

I conducted spatial analyses of 20th-century climate change and a meta-analysis of 123 peer-reviewed scientific articles published from January 1990 to June 2010 that use data from national parks to analyze historical impacts of climate change, future projections, and carbon stocks and emissions. A systematic search of the ISI Web of Knowledge database of more than 98 million scientific references generated this set of articles (table 1). For articles that examined historical change, I evaluated their use of three procedures that furnish increasing levels of scientific evidence:

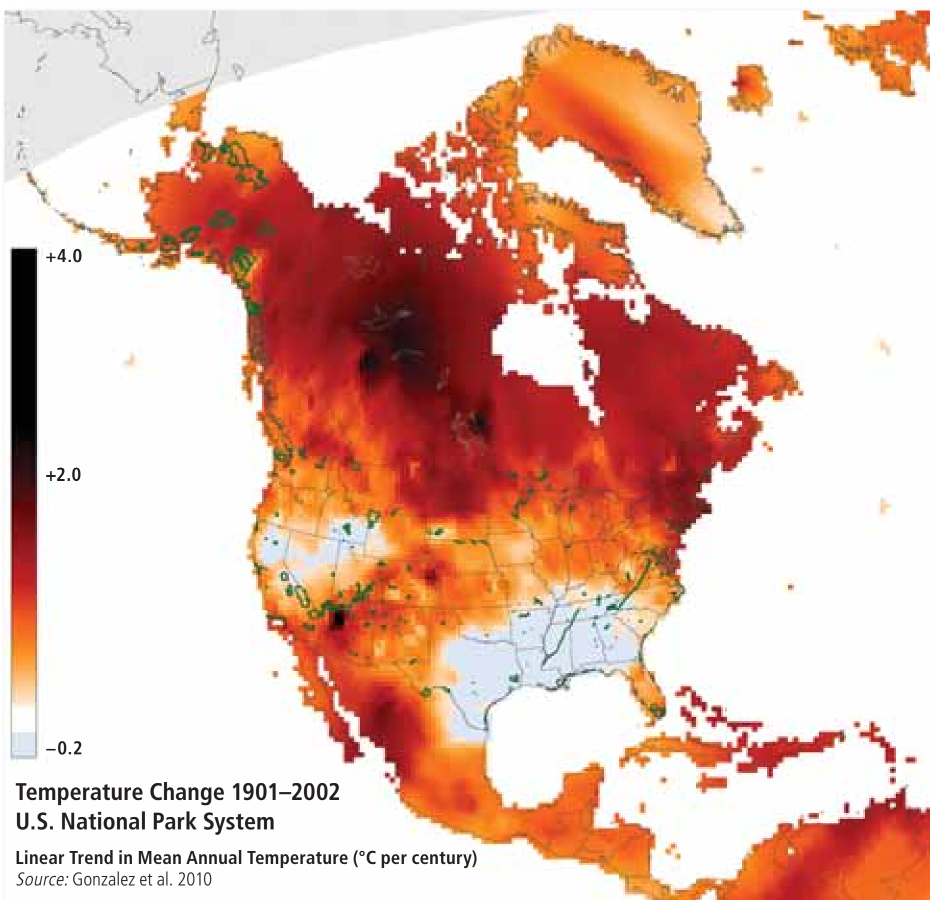

Figure 1. Ninety-six percent of National Park Service land area and 84% of units are in areas of observed 20th-century warming, shown here. Of these, 51% of land and 64% of units are in areas of statistically significant warming attributed to human emissions of greenhouse gases.

Table 1. Published climate change research from national parks

Type of Research	Definition	Publications	Number of National Park System Units	Key Results
All publications	Peer-reviewed scientific articles published since 1990 that use data from national parks to analyze aspects of climate change	123	189	Parks with data used in greatest number of publications: Yellowstone National Park (29) Yosemite National Park (26) Glacier National Park (24) Rocky Mountain National Park (22) Grand Teton National Park (16) Olympic National Park (15) Sequoia National Park (14) North Cascades National Park (13) Lassen Volcanic National Park (12) Zion National Park (12)
Historical impacts	Research examining ecological changes in the 19th and 20th centuries	87	163	82% of studies that quantified historical data found change consistent with climate change
No analysis of change	Research that did not quantify change	3	9	
No change observed	Research that quantified change, but the variable studied did not change or followed interdecadal cycles	13	18	
Observation	Recording of differences over time with no statistical analysis or with less than 30 years of data	43	137	40 observed changes consistent with climate change
Detection	Measurement of historical changes that are statistically significantly different from natural variability	27	93	100% of changes were consistent with climate change
Attribution	Determination of the relative importance of different factors in causing detected changes	11	85	100% of changes were attributed to climate change
Projections	Modeled simulations of future conditions based on assumptions of factors and trends	23	41	Projected shifts of Joshua tree (*Yucca brevifolia*) and many mammal species
Carbon	Stocks and flows of carbon in vegetation and emissions from fossil fuel burning	13	130	Redwood and Sequoia National Parks have highest forest carbon densities in the world

Note: The total number of publications is the sum of the three major categories (historical impacts, projections, and carbon). The table also shows numbers of publications for subcategories of historical impacts. Many park units appear in multiple categories and subcategories, so those totals are not additive.

observation, detection, and attribution (see definitions in table 1).

Physical impacts

Ninety-six percent of NPS land and 84% of National Park System units are in areas of observed 20th-century warming (fig. 1). Mean annual temperature increased 0.6 ± 0.5°C (1.1 ± 0.9°F) from 1901 to 2002 in the areas where NPS units are located. Fifty-one percent of NPS area and 64% of National Park System units are in areas of statistically significant warming. Twenty percent of NPS-administered area and 24% of National Park System units are in areas of detected change in precipitation, with half the area experiencing increases and half experiencing decreases. Analyses of human and natural factors attribute 93% of detected global warming to human emissions of greenhouse gases (IPCC 2007a).

Data from weather stations and snow courses in 53 national parks in the western United States have contributed to detection of physical changes in the last half of the 20th century and attribution of these to climate change, including increased winter temperatures (Barnett et al. 2008; Bonfils et al. 2008), decreased snowpack (Barnett et al. 2008; Pierce et al. 2008), decreased ratio of snow to rain (Pierce et al. 2008), earlier spring warmth (Ault et al. in press), and earlier spring streamflow (Barnett et al. 2008). Data from snow courses and tree rings in nine national parks in the Rocky Mountains have contributed to the detection of 20th-century melting of mountain snowpack, including glaciers in Glacier (Montana) and North Cascades (Washington) National Parks, that is attributable to climate change (Pederson et al. 2011).

In addition, 155 years of sea-level measurements from the San Francisco tide gauge at Golden Gate National Recreation Area (California) provide the longest sea-level time series in the Western Hemisphere. The gauge has detected a sea-level rise of 14 cm (5½ in) per century (Church and White 2006; fig. 2), attributed to climate change (Hegerl et al. 2007).

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Figure 2. In Golden Gate National Recreation Area, sea level at the San Francisco tide gauge (far shore, center) has increased at a rate of 14 cm (5.5 in) per century from 1854 to 2010, with analyses attributing the rise to climate change. Graph: Sea level at the gauge, showing a statistically significant increase (thin blue line: annual average, thick blue line: running five-year average, black line: linear trend, in centimeters above or below 1964 mean sea level).

Ecological impacts

Field measurements from national parks have contributed to detection of 20th-century ecological changes attributed to climate change. Winter ranges of numerous bird species have shifted an average of 0.5 ± 2.4 km (0.3 ± 1.5 mi) per year northward from 1975 to 2004 in 54 national parks across the United States (La Sorte and Thompson 2007). Conifer tree background mortality has increased in Mount Rainier (Washington), Olympic (Washington), Sequoia (California), and Yosemite (California) National Parks (van Mantgem et al. 2009). The boreal conifer forest biome has shifted into the tundra biome in Noatak National Preserve (Alaska) (Suarez et al. 1999) and into the alpine biome in Yosemite National Park (Millar et al. 2004). Small-mammal ranges have shifted upslope approximately 500 m (550 yd) in Yosemite National Park (Moritz et al. 2008; fig. 3).

Research has detected other 20th-century ecological impacts in national parks that have not been explicitly attributed to climate change, but are consistent with climate change and scientific understanding of ecological responses to warming. Wildfire frequency and duration have increased in 27 national parks in the West. Numerous plant and bird species have shifted either upslope or downslope, tracking changes in temperature and precipitation, in six national parks in California. Conifer growth has increased in Lake Clark National Park and Preserve (Alaska) and at high elevations in Yosemite National Park. Extensive tree die-off shifted the ecotone between piñon–juniper woodland (*Pinus edulis* and *Juniperus monosperma*) and ponderosa pine (*Pinus ponderosa*) forest in Bandelier National Monument (New Mexico).

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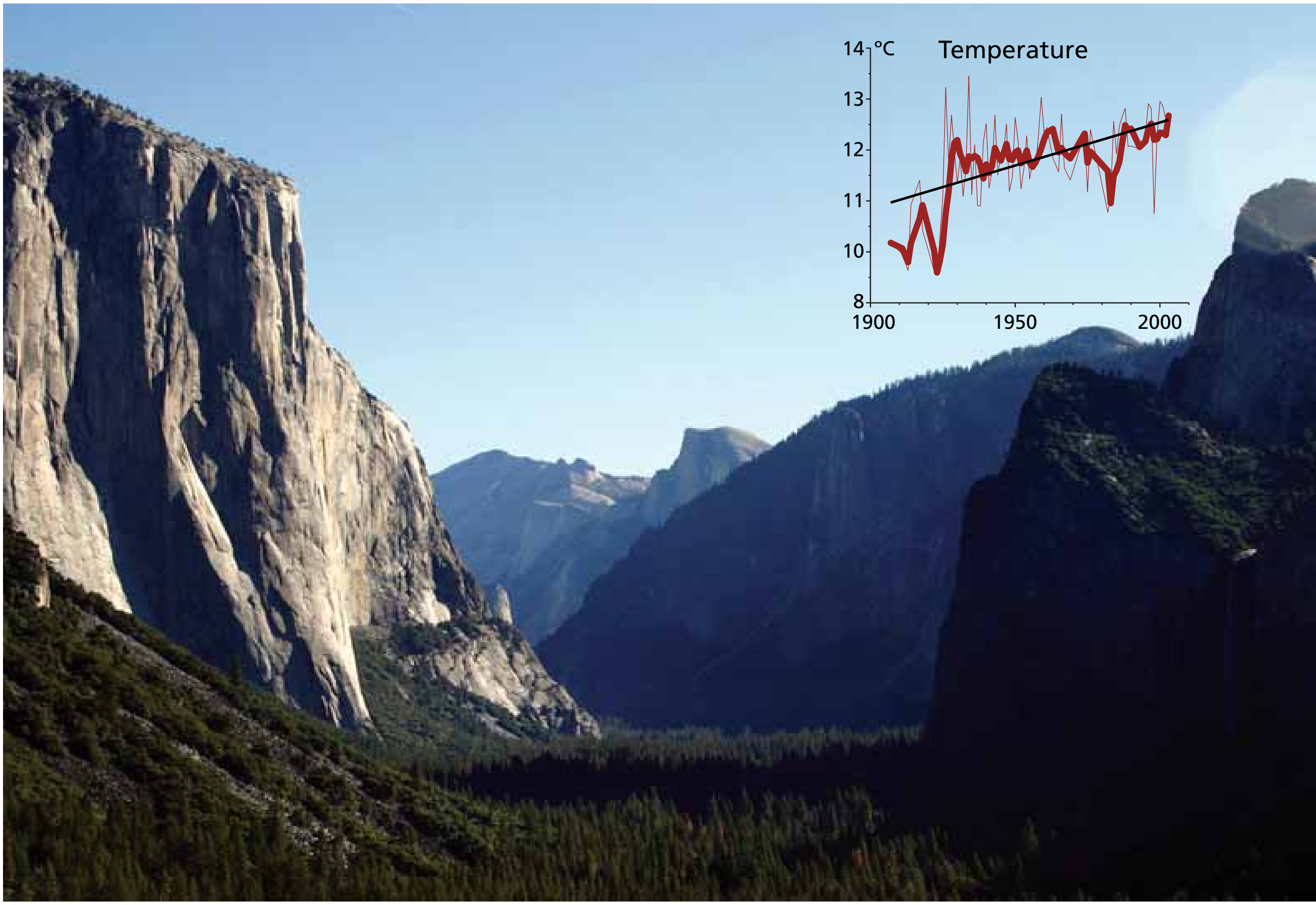

Figure 3. In Yosemite National Park, ranges of numerous small mammals have shifted upslope from 1920 to 2006, with analyses attributing the shift to climate change. Graph: Average annual temperature at the Yosemite headquarters weather station, showing a statistically significant increase from 1907 to 2003 (thin red line: annual average, thick red line: running five-year average, black line: linear trend).

Other research has observed 20th-century ecological impacts consistent with climate change, but either has not tested the changes for statistical significance or has measured the changes for periods of less than 30 years. Breeding ranges of numerous bird species have shifted northward in 40 national parks and other lands in the East. Extensive dieback has reduced piñon pine woodlands in 19 national parks and other lands across the Southwest. Area burned by wildfire has increased in 16 national parks in Alaska. Conifer trees have shifted upslope in Glacier, Lassen Volcanic, Olympic, and Yellowstone National Parks. Flowering of cherry trees and other plant species has advanced in the National Capital Parks, Rock Creek Park, and other locations in the Washington, D.C., area. Stream nitrate concentrations have increased in Rocky Mountain National Park as glacial melt exposes sediments with elevated nitrogen. Amphibian species richness has declined in Yellowstone National Park (Wyoming, Montana, and Idaho) due to wetland desiccation. High ocean temperatures have bleached and killed coral in Biscayne National Park (Florida), four national parks in the U.S. Virgin Islands, and other locations in the Caribbean.

Carbon

Ecosystems can naturally reduce global warming by removing carbon dioxide from the atmosphere and storing it in biomass, one of many ecosystem services that national parks provide. Measurements of coast redwood (*Sequoia sempervirens*) in Humboldt Redwoods State Park (California), just south of Redwood National Park (Busing and Fujimori 2005), and giant sequoia (*Sequoiadendron giganteum*) in Sequoia National Park (Blackard et al. 2008) show that groves of these two species contain carbon at the highest densities in the world (Aalde et al. 2006).

Field measurements by the USDA Forest Service in 128 national parks across the country, combined with remote sensing, have produced a spatial data layer of forest carbon density for the U.S. (Blackard et al. 2008). The results show that forest carbon densities are highest in Redwood and Sequoia National Parks and high in the Pacific Northwest. Detailed studies have examined the effects of fire, windthrow, and other disturbances on carbon dynamics in Everglades (Florida), Great Smoky Mountains (North Carolina and Tennessee), Hawaii Volcanoes, Yellowstone, and Zion (Utah) National Parks. Fossil fuel emissions inventories in the first 18 national parks in the Climate Friendly Parks program (a nonrandom sample that covers one-tenth of NPS land area and accounts for one-fifth of NPS visitors) estimated total emissions equivalent to a U.S. city of 21,000 people (Steuer 2010). Visitor car driving within parks accounts for two-thirds of estimated emissions.

Projections

Projections of potential future impacts of climate change help to analyze future vulnerabilities, but are subject to uncertainties in the three types of models involved in projection: (1) greenhouse gas emissions scenarios, (2) general circulation models of climate responses to emissions, and (3) impacts models of ecological responses to climate. Furthermore, the sparse density of weather stations in many areas can preclude spatial downscaling of coarse model outputs to the fine resolutions needed for park planning. Numerous publications project potential future impacts in national parks, such as shifts of suitable growing conditions for the Joshua tree (*Yucca brevifolia*) out of Joshua Tree National Park in California (Cole et al. 2011) and continued shifts of mammal habitats in eight national parks around the country (Burns et al. 2003).

Application of climate change science to resource management

Detection can answer the basic management question of whether or not a resource is changing. Attribution can guide resource management toward the predominant factor that is causing change. Whereas resource managers have developed many measures that address urbanization, invasive species, grazing, fire, timber harvesting, and other non-climate factors, changes attributed to climate change might require new adaptation measures. Detection and attribution also provide key information for vulnerability analyses, which examine the exposure, sensitivity, and adaptive capacity of a resource. The most effective vulnerability analyses combine observations and projections of climate and resources to identify locations of vulnerable areas and potential refugia. Vulnerability analyses for 22 national parks in coastal areas (Pendleton et al. 2010) and for Joshua trees (*Yucca brevifolia*) in Death Valley National Park, Joshua Tree National Park, and Mojave National Preserve (all California) and other areas (Cole et al. 2011) provide spatial data for prioritizing the location of future adaptation measures. Finally, scientific research that quantifies emissions from fossil fuel use and forest carbon densities in natural ecosystems can help the National Park Service to reduce the production of greenhouse gases that cause climate change.

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