

# PARKScience

Integrating Research and Resource Management in the National Parks

National Park Service  
U.S. Department of the Interior

Natural Resource Stewardship and Science  
Office of Education and Outreach



## CLIMATE CHANGE SCIENCE IN THE NATIONAL PARKS

Concluding our two-issue focus on climate change, this edition explores what we know, how we know it, and what this suggests for park management



- **Pikas in peril**
- **Climate change research synthesis**
- **Everglades and sea-level rise**
- **Glacier changes and effects at Mount Rainier and Denali**
- **Alpine plant communities**
- **Value in phenology monitoring**
- **Vegetation changes at Grand Canyon**

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# From the Editor

## Climate science in the spotlight

This edition completes our two-issue examination of climate change, focusing on what we know about it and what this knowledge means for park management. Science is critical to understanding the effects of climate change and for analyzing the vulnerability of parks, and is the basis for park management decisions. This look at the science of climate change complements our discussion last spring of adaptation and mitigation strategies for dealing with climate change and the importance of engaging and communicating with the public. Like that issue, this one shares many examples of how park managers are responding to the challenge.

I am not surprised that a resource management issue as universal as climate change garnered articles about parks in the Arctic and subtropics and from sea level to the alpine life zone. Though varied, these articles highlight several pertinent themes. For example, a suite of scientific disciplines and methods are needed to investigate and understand climate change and its effects on parks. Vulnerability assessments are important to identify the susceptibility of resources and to prioritize actions. Models are important, but field observations over long time periods are essential. Climate change science is complex and the demand for it so vast that it is best met through collaboration. A corollary is that with so much information pouring in, scientists need to help managers synthesize and assimilate it into park scenarios.

For me the overriding theme is that climate change is transforming park management in scope and scale and by presenting very tough questions. For example, research projects designed to understand and enhance species resilience may also help address the uncertainties of when to intervene and to what extent, but these remain difficult management judgments. Also, how should we document and prepare for the possibility of natural and cultural resource loss? Given the pervasiveness of climate change and human influence on nature that are outside our control, how should we interpret policies for managing natural systems?

Science is crucial to exploring these issues and supporting park management in addressing them.



Another intriguing facet of this issue is the contrast between the complexity of the science that demonstrates resource change or vulnerability in some articles and the simplicity of the photos. No article exemplifies this more than the feature on changes in Denali's glaciers. Repeat photography reveals dramatic changes in a subset of these

glaciers, but only the science tells the more complete and complex story of climate interactions. It takes experts to unravel the story just as it does to communicate it. Climate change is an issue that requires both to facilitate public understanding.



**A thousand words—but which ones?** The effects of climate change on glaciers in Denali National Park are complex. Repeat photography is one technique that helps scientists understand the scale and distribution of the changes.

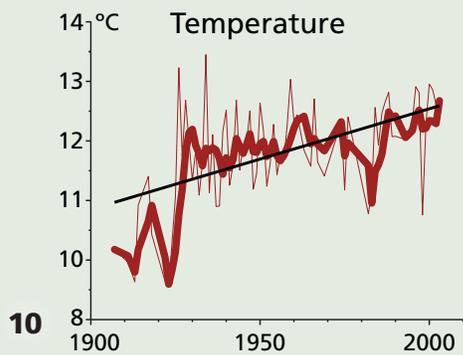
—Jeff Selleck

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## ON THE COVER

Facing range contraction because of its sensitivity to rising temperature, the American pika is an indicator species for climate change. National Park Service staff and university researchers have teamed up to study and assess the vulnerability of pikas to climate change in eight national parks, including Craters of the Moon National Monument and Preserve, Idaho, this pika's home.

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NATALIE MELASCHENKO, SOUTHERN COLORADO PLATEAU NETWORK



### >> Masthead (continued from page 2)

*Park Science* is a research and resource management bulletin of the U.S. National Park Service. It reports the implications of recent and ongoing natural and social science and related cultural research for park planning, management, and policy. Seasonal issues are published usually in spring and fall, with a thematic issue that explores a topic in depth published annually in summer or winter. The publication serves a broad audience of national park and protected area managers and scientists and provides public outreach. It is funded by the Associate Director for Natural Resource Stewardship and Science.

Articles are field-oriented accounts of applied research and resource management topics that are presented in nontechnical language. They translate scientific findings into usable knowledge for park planning and the development of sound management practices for natural resources and visitor enjoyment. The editor and board review content for clarity, completeness, usefulness, scientific and technical soundness, and relevance to NPS policy.

Article inquiries, submissions, and comments should be directed to the editor by e-mail; hard-copy materials should be forwarded to the editorial office. Letters addressing scientific or factual content are welcome and may be edited for length, clarity, and tone.

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## UPCOMING ISSUES

### Fall 2011

Seasonal issue. December release. In production.

### Winter 2011–2012

January 2012 release. Topical issue: Wilderness research and management. In production.

### Spring 2012

Seasonal issue. May release. Contributor's deadline: 15 January.

Visit [http://www.nature.nps.gov/ParkScience/](http://www.nature.nps.gov/ParkScience) for author guidelines or contact the editor ([jeff\\_selleck@nps.gov](mailto:jeff_selleck@nps.gov) or 303-969-2147) to discuss proposals and needs for upcoming issues.

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# Information Crossfile\*

## SUMMARIES

### The climatic envelope: Understanding the thermo-geographic range of the mighty wolverine

**THE AUTHORS OF THIS STUDY POSE THE QUESTION: HOW** does environmental temperature and snow cover affect the geographic range in which the wolverine (*Gulo gulo*) can survive and reproduce? Past research associated wolverine reproductive denning and snow cover on a small scale (15 dens), but it did not explore how this association could limit the wolverine over its entire range. The methods that Copeland et al. (2010) used to answer the question provide an instructive scientific and anecdotal dissection of the “bioclimatic envelope” model of species distribution. According to the authors, the bioclimatic envelope model is often criticized for not accurately reflecting biotic factors such as the behavior and physiology of the target species, thus leading to overly simplistic correlations between geographic range and climatic requirements. Copeland et al. (2010), with “reliable understandings” of the wolverine’s geographic range and its climatically linked biological needs, such as the species’ obligate reliance on the spring snowpack, vouch that they have evaluated whether the wolverine’s current range is consistent with climatic conditions without such gaps in knowledge. Furthermore, the authors address the limitations of the bioclimatic envelope model by comparing model results with on-the-ground research.

Wolverine live throughout the Arctic and in subarctic areas and boreal forests of Eurasia and North America, and their bodily apparatus is adapted to those environs: a compact body carried by broad plantigrade feet and insulated by a dense coat enables quick travel through soft snow. In particular, the snow cover during peak denning season, early February to early May, provides a thermal blanket that aids the survival of young wolverines—but is it absolutely critical to wolverines’ reproductive denning habitat? And is the wolverine’s range limited by a mean temperature in that region? To find out, Copeland et al. (2010) surveyed spring snow cover over a seven-year period in the Northern Hemisphere, gained from satellite imaging data, and cross-referenced that information with precise wolverine den locations tracked by the Scandinavian wolverine den monitoring program and all known den locations in Finland and North America. Also evaluated were the upper thermal limits of the species: average maximum August temperatures for the years 1950–2000 and summer wolverine sightings. The results, encompassing 562 wolverine den sites in all, show that 97.9% of the den sites occurred in areas

where spring snow was present at least one of seven years. That is, virtually all wolverine reproductive dens in the study occurred within the spring snow coverage. A few sites outside of the spring snow coverage had adequate snowdrifts to accommodate reproductive dens though the snow areas were negligibly small.

The spatial agreement of wolverine den locations with summer temperature coverage supports the hypothesis that wolverines redistribute to cooler environments during hot summer months in southern portions of their range. When the deep, persistent snow surrounding their dens diminishes upon earlier spring snow melt and increasing summer temperatures, the availability of summer habitats may be reduced—a direct threat to the wolverine’s breeding viability and geographic distribution.

As the polar bear copes with waning ice floes, the wolverine may struggle with reduced snow coverage. The authors note that “significant reductions in spring snow cover associated with climate warming have already occurred in some portions of the wolverine’s range in the contiguous United States,” which could lead to a reduction in wolverine habitat and an associated loss of connectivity between populations. Though the wolverine is notoriously averse to human development, the authors suggest that physiological investigations into critical temperatures for the wolverine could be important for understanding and anticipating the potential impacts of climate change on wolverine distribution and survival.

### Reference

Copeland, J. P., K. S. McKelvey, K. B. Aubry, A. Landa, J. Persson, R. M. Inmann, J. Krebs, E. Lofroth, H. Golden, J. R. Squires, A. Magoun, M. K. Schwartz, J. Wilmot, C. L. Copeland, R. E. Yates, I. Kojola, and R. May. 2010. The bioclimatic envelope of the wolverine (*Gulo gulo*): Do climatic constraints limit its geographic distribution? *Canadian Journal of Zoology* 88:233–246. doi:10.1139/Z09-136.

—Jonathan Nawn and Amy Stevenson



### Loss assessment: Amphibians of the Western Hemisphere

**NOWHERE TO RUN, NOWHERE TO HIDE. AS CLIMATE** change raises the surface temperatures of lakes, ponds, and streams and alters the seasonal precipitation of adjacent landmasses, a class of animal that relies on freshwater habitats—amphibians—is intensely threatened. Because of their physiological sensitivity to temperature, water-permeable skin, and migration and breeding behavior tied to precipitation patterns, amphibians,

\*Information Crossfile synthesizes selected publications relevant to natural resource management. Unless noted, articles are not reviewed by reference source author(s).

according to Lawler et al. (2010), are likely to be “highly sensitive” to climatic shifts toward warmer, drier regimes in freshwater ecosystems.

Amphibians occur in three orders: anurans (frogs and toads), caudates (newts and salamanders), and the lesser-known gymnophonia (caecilians), and their numbers already are reported to be suffering. The International Union for Conservation of Nature lists more than 32% of the world’s amphibians as vulnerable, endangered, or critically endangered. Also, estimates suggest that 122 species have gone extinct since 1980. The leading cause of these population declines is generally considered to be habitat loss. But before a prognosis can be given, the question must be asked: Where does it hurt the most? By zeroing in on the geographic vulnerability of amphibians relative to climate change, the authors provide broad-scale guidance for directing conservation efforts.

Using bioclimatic models, species distribution data, and future climate change simulations, the authors map areas in the Western Hemisphere where amphibians are “particularly likely to be affected by climate change.” Bioclimatic models provide a general indication of future climate-driven shifts in amphibian habitats. The scientists ran 20 future climate simulations based on 37 bioclimatic variables, including scenarios for low and high amounts of greenhouse gas emissions, to determine changes in temperature and precipitation. These model simulations were then overlaid with the distributions of 1,099 amphibian species that could not be modeled accurately because of their limited ranges.

Collectively, future climate changes projected by the authors showed that amphibian species in the Western Hemisphere exhibited larger range contractions than range expansions. A net loss in total range area was projected for 85% of all species. Specifically, species turnover—the percentage change in species in an area—will be highest in the Andes Mountains and parts of Central America and Mexico. Also, much of Mexico, and Central and South America were projected to experience decreases in precipitation in at least one season, with likely consequences for amphibians. Most of the 79 ecoregions modeled were projected to experience at least a 30% turnover in amphibian species. In the eastern United States, a 50% turnover was projected. A minor finding of the study is that range increases may occur for a few species, presumably because warmer areas may be suitable where the environment had heretofore been too cold.

The authors translate this information into management strategies based on the likelihood of range contractions and expansions and the relative sizes of each. For most species (where range contractions are likely to be larger than range expansions), simply focusing on preserving the populations in areas that are projected to

experience less change may be an option. For species with limited dispersal capabilities, small populations, or where range contractions and expansions are likely to be large, translocations to new habitat may be necessary.

Disease is another factor that affects amphibians and works in tandem with climate change, though the interactions are complex. Additionally, climate change may result in the movement of amphibian predators, prey, and competitors, affecting the suitability of any given habitat. Unfortunately for amphibians, the hits will keep coming.

It is worth noting, however, that bioclimatic models have a number of limitations. They cannot account for pure adaptability of species, which can lead to overestimating range shifts. Plus, they are only as good as the data. In this application, the data reflect known niches of amphibians and may miss areas that could be habitable. Also, species that have been extirpated locally because of factors other than climate change are not represented. These factors and other biotic interactions that are not considered could have a large effect. Thus, while they can provide broad approximations of climatic effects, models “cannot necessarily accurately predict the future location of a given species,” according to the authors.

Despite these limitations, Lawler et al. (2010) argue that the results of their study demonstrate that over the coming century there will be major shifts in the various ranges of amphibians. These results provide a solid case for increasing analyses of range shifts and other complementary evaluations, such as scenarios for precipitation change and greenhouse gas emissions.

## Reference

Lawler, J. J., S. L. Shafer, B. A. Bancroft, and A. R. Blaustein. 2010. Projected climate impacts for the amphibians of the Western Hemisphere. *Conservation Biology* 24(1):38–50.

—Jonathan Nawn, Amy Stevenson, and Jeff Selleck



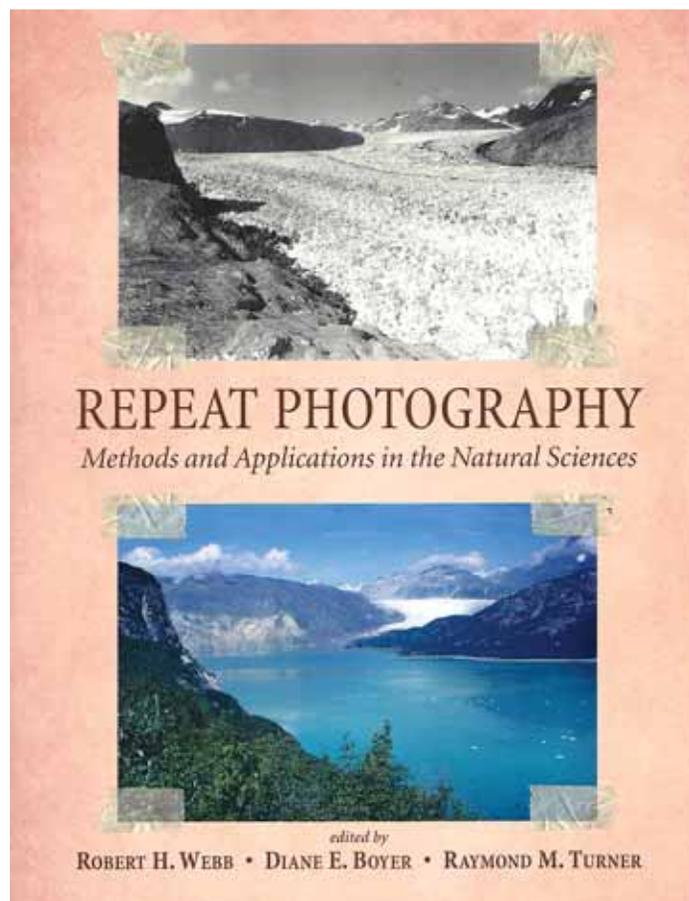
## BOOK PROFILE

*Repeat Photography: Methods and Applications in the Natural Sciences*

**IF A PICTURE IS WORTH A THOUSAND WORDS, IMAGINE** how much data can be gleaned from a decade of sequential pictures. Repeat photography, which is described in this reference book of the same name as “nearly as old as photography itself,” has evolved from a way to track the movement of glaciers—around 1888—to a modern field of study with “broad scientific, cultural, and historical applications.” The practice of taking multiple photos of the same natural resource from the same vantage point over a length of time, often many years, enables resource managers and scientists to document vegetation density and evaluate ecological and geologic changes in landscapes. According to editors Robert Webb, Diane Boyer, and Raymond Turner (2010), more than two decades have elapsed since a similar work focusing solely on repeat photography was published. Since that time, the field has “exploded with new methods, new areas of application, and new questions.” The editors note, however, that technological advances such as satellite remote sensing will likely not be available to developing countries with limited budgets. So, they say, the “point and shoot” method will have to suffice. And so it does.

After all the pointing and shooting, the real work begins. The authors discuss how analysis of repeat photography can be used in conjunction with detailed ecological surveys to provide a robust and accessible qualitative and quantitative measure of environmental change. In 23 chapters and with 100 photo sequences, scientists from five continents contributed articles that discuss techniques, geologic and geomorphic uses, applications in population ecology and landscape change, and relevance to societal concerns or reconstructions of changes in cultural features. A large portion of the book is dedicated to the applications of repeat photography in areas such as geoscience, geomorphology and glacier movement, the long-term stability of archaeological sites, population ecology, climate change, and cultural development.

Repeat photography’s most often used application is to acquire baseline information on the stability of vegetation to document ecosystem change. “Knowledge of vegetative conditions and trends is essential for informed management of wildlife. Lacking such knowledge, managers tend to accept current vegetative conditions as the norm, not understanding that wildlife habitats have undergone pronounced changes,” writes George E. Gruell in the book’s foreword. An example of the results possible with the use of this technique is illustrated (by Webb) in a research report on Grand Canyon National Park in this issue of *Park Science* (see page 83).



The book also explores where repeat photography is headed as technology evolves. High-resolution film and digital media are permanent benchmarks in repeat photography, and the implications of archival storage systems that guarantee longevity of the data are broad. The authors also discuss the use of GIS (Geographical Information System) in repeat photography analyses.

In this comprehensive text about past and current methods and uses of repeat photography, the editors have compiled essays and studies that exhibit the scientific ends to which repeat photography, an inherently interdisciplinary field of study, is the means. “As a scientific tool, repeat photography is unique in that it can be used to both generate and test hypotheses regarding ecological and landscape changes, sometimes with the same set of changes,” write Webb et al. (2010).

**Reference**

Webb, R. H., D. E. Boyer, and R. M. Turner. 2010. *Repeat photography: Methods and applications in the natural sciences*. Island Press, Washington D.C., USA.

—Jonathan Nawn and Amy Stevenson

# State of Science

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

By Patrick Gonzalez

### EMISSIONS FROM HUMAN ACTIVITIES

have increased atmospheric concentrations of greenhouse gases, causing an increase in global average surface temperature of  $0.7 \pm 0.2^\circ\text{C}$  ( $1.3 \pm 0.4^\circ\text{F}$ ) 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

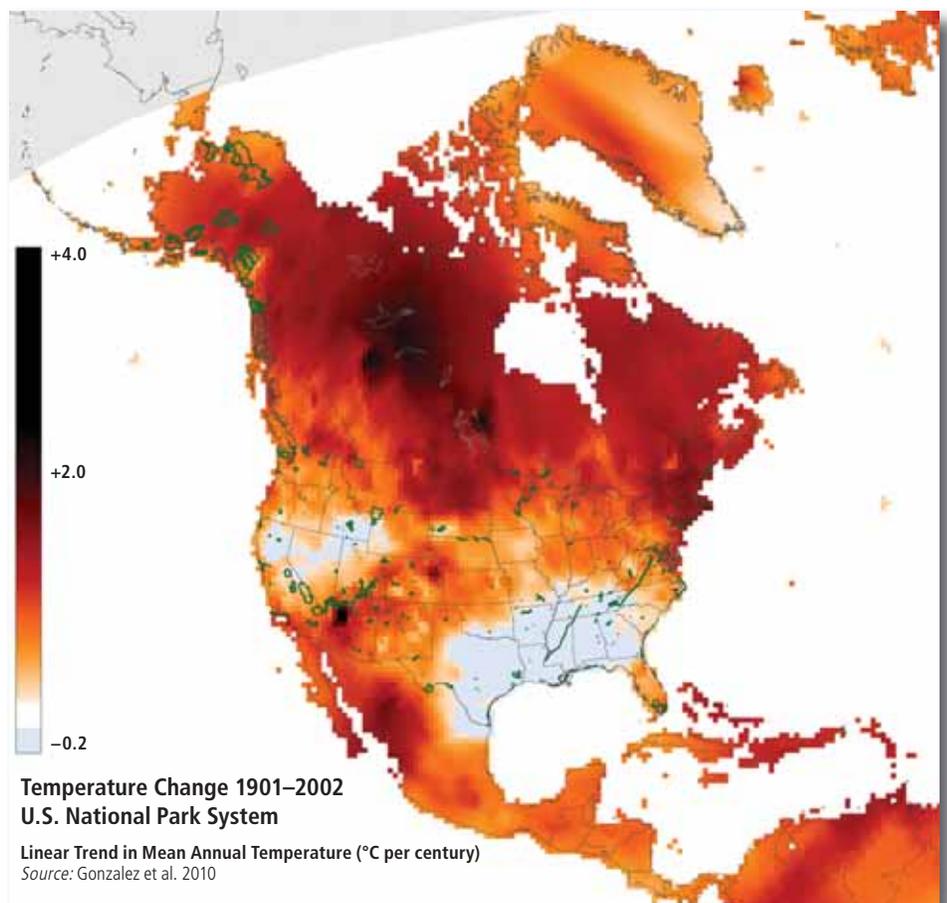
I conducted spatial analyses of 20th-century climate change and a meta-analysis of 123 peer-reviewed scientific articles published from January 1990 to June 2010 that use data from national parks to analyze historical impacts of climate change, future projections, and carbon stocks and emissions. A systematic 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.

### 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  $0.6 \pm 0.5^\circ\text{C}$  ( $1.1 \pm 0.9^\circ\text{F}$ ). 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



**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 ( <i>Yucca brevifolia</i> ) 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  $0.6 \pm 0.5^\circ\text{C}$  ( $1.1 \pm 0.9^\circ\text{F}$ ) 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 ( $5\frac{1}{2}$  in) per century (Church and White 2006; fig. 2), attributed to climate change (Hegerl et al. 2007).

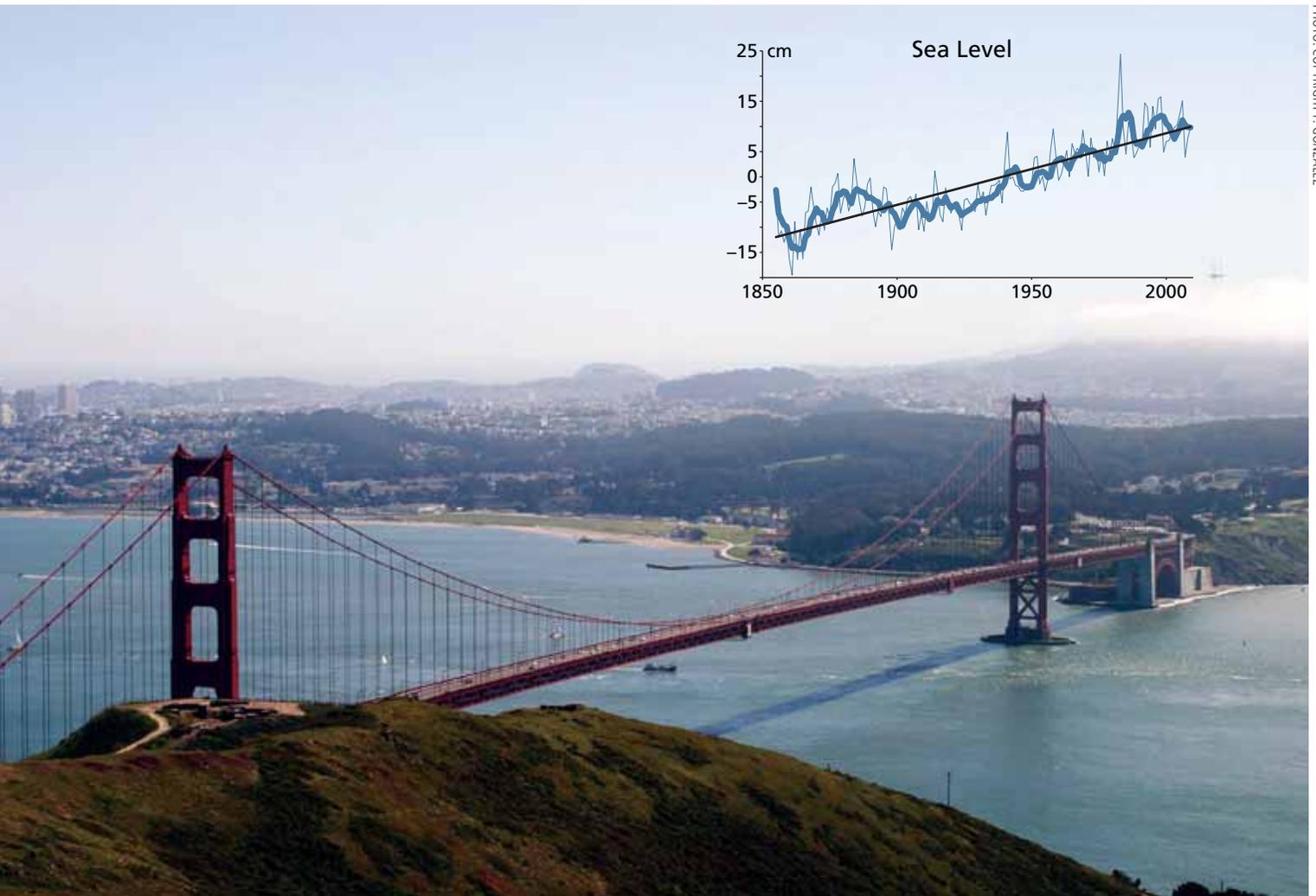


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**Figure 2.** In Golden Gate National Recreation Area, sea level at the San Francisco tide gauge (far shore, center) has increased at a rate of 14 cm (5.5 in) per century from 1854 to 2010, with analyses attributing the rise to climate change. Graph: 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

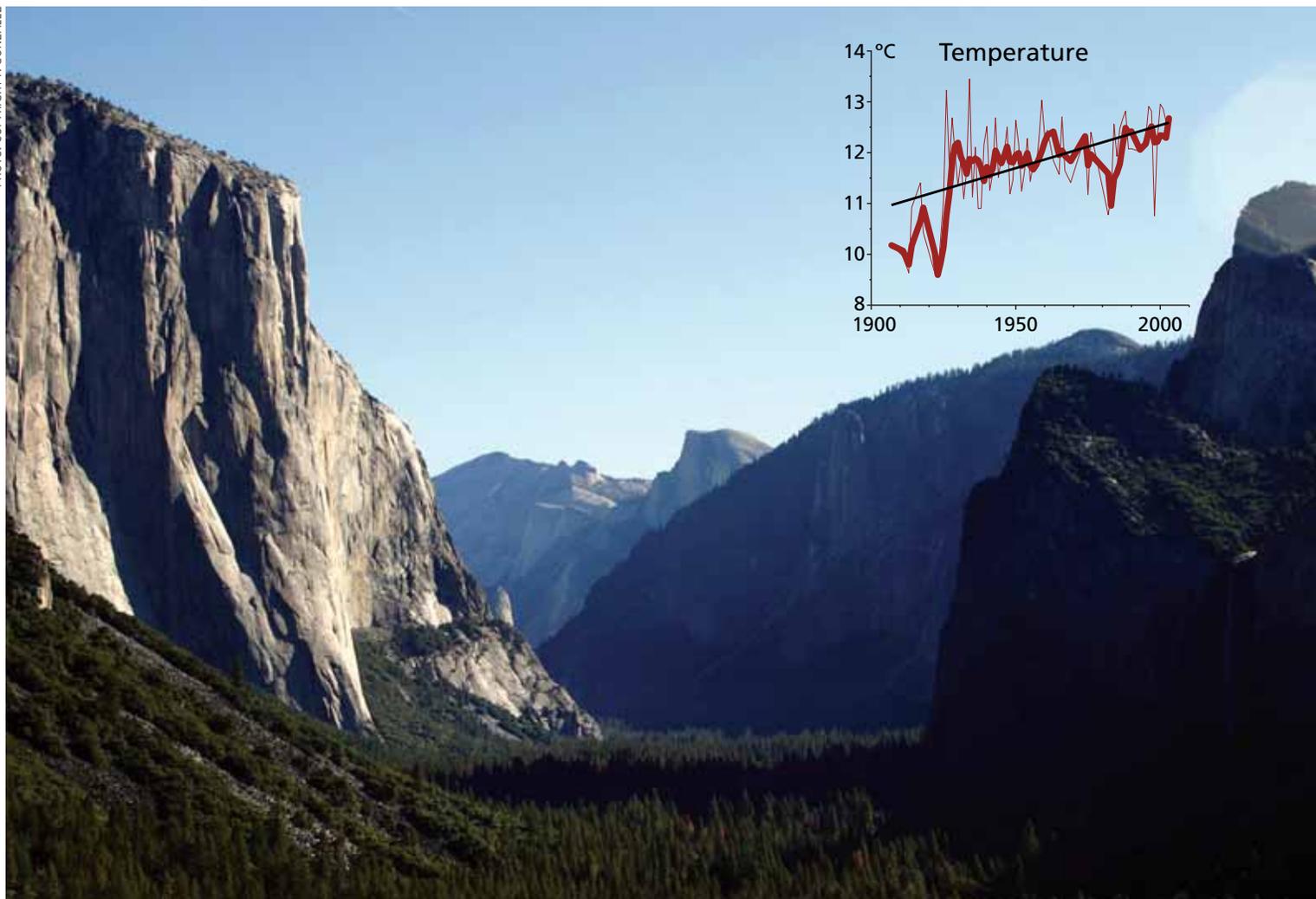
Field measurements from national parks have contributed to detection of 20th-century ecological changes attributed to climate change. Winter ranges of numerous bird species have shifted an average of  $0.5 \pm 2.4$  km ( $0.3 \pm 1.5$  mi) per year northward from 1975 to 2004 in 54 national parks across 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. Wild-

fire 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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## Climate change–related definitions

**Climate**—The mean state of the atmosphere over a long period of time. This period is generally at least 30 years, to produce a statistically significant sample and to avoid shorter term variability. The principal elements of climate are the same as the principal elements of weather (IPCC 2007a).

**Climate change**—Alteration in the mean state of the atmosphere over a long period of time that can be detected statistically. Climate change consists of trends in the mean and the variability of climate that persist for an extended period, typically decades or longer. Climate change may be due to natural internal processes, natural external forcings, or persistent anthropogenic changes in the composition of the atmosphere or in land use (IPCC 2007a).

**Climate variability**—Variations in the mean state of the atmosphere on all spatial and temporal scales beyond the scales of individual weather events. Climate variability may be due to natural internal processes within the climate system (internal variability) or to variations in natural or anthropogenic external forcing (external variability). Major forms of interdecadal variability, which are often cyclical, include the El Niño–Southern Oscillation and the Pacific Decadal Oscillation (IPCC 2007a).

**Global warming**—A long-term increase in the average surface temperature of the world that constitutes the major form of climate change.

**Radiative forcing**—Change in the net radiation flow at the top of the troposphere (about 6–10 km [4–6 mi] altitude), with positive values indicating increased heat toward the surface of Earth (IPCC 2007a). Changes in greenhouse gases, ozone, other atmospheric constituents, airplane contrails, the reflectivity of the earth, and the output of the sun contribute to radiative forcing. Radiative forcing from 1750 to 2005 was +1.6 watts per square meter [+0.8, –1.0 watts per square meter], causing the warming detected around the world (IPCC 2007a). Greenhouse gas emissions from power plants, motor vehicles, deforestation, and other human activities have caused 93% of the radiative forcing (IPCC 2007a).

**Weather**—The state of the atmosphere at a point in time. Principal elements of weather include temperature, precipitation, wind, air pressure, and humidity (U.S. National Weather Service, <http://www.weather.gov/glossary>).

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# Pikas in Peril

## Multiregional vulnerability assessment of a climate-sensitive sentinel species



By Lisa Garrett, Mackenzie Jeffress,  
Mike Britten, Clinton Epps, Chris Ray,  
and Susan Wolff

**Figure 1.** Many believe that pikas only occur in high-elevation talus habitat. However, the American pika can be found as low as sea level, especially in the northern portion of its range, and in other fragmented rock structures, such as the lava beds found at Craters of the Moon National Monument and Preserve (illustrated) and Lava Beds National Monument.

NPS/DOUG OWEN

### RESOURCE MANAGERS FROM EIGHT

western national parks and three universities are collaborating on a research project to document American pika (*Ochotona princeps*) occurrence, predict distribution patterns, measure gene flow and connectivity of populations, and assess vulnerability of pika to climate change (fig. 1). This joint research is made possible through funding from the National Park Service Climate Change Response Program.

Parks included in this project encompass a wide variety of habitat and elevation ranges from talus slopes in alpine areas in the Rocky Mountains to lower-elevation lava flows in the Columbia Basin and Cascades. Pika researchers are collecting data for this project in Crater Lake National Park (Oregon), Craters of the Moon National Monument and Preserve (Idaho), Grand

### Abstract

A large team of National Park Service (NPS) staff and academic researchers are collaborating on a three-year research project funded through the NPS Climate Change Response Program. The "Pikas in Peril" research team hopes to address questions regarding the vulnerability of the American pika (*Ochotona princeps*), a species sensitive to temperature and climate, to future climate change scenarios projected for the western United States. The project objectives are to (1) document pika occurrence patterns and predict pika distribution across eight national parks in the western United States; (2) measure gene flow and model connectivity of pika populations in five of those parks; and (3) project climate change effects on the future distribution, connectivity, and vulnerability of pika populations in each park. Systematic pika occupancy surveys were conducted in 2010 and 2011 across a range of latitudes, longitudes, elevations, and substrate types (talus slopes vs. lava beds). Analyses of DNA extracted from fecal pellets collected during occupancy surveys will document recent gene flow patterns. The distribution, habitat, connectivity, and genetic data and models will be combined to conduct a quantitative vulnerability assessment that explicitly predicts pika response to climate change. By assessing the vulnerability of this sentinel species, the research team will provide park managers with insights into the expected rate and magnitude of climate-related changes in park ecosystems and critical information for park scenario planning and interpretive goals.

### Key words

American pika, monitoring, occupancy, *Ochotona princeps*, vulnerability assessment

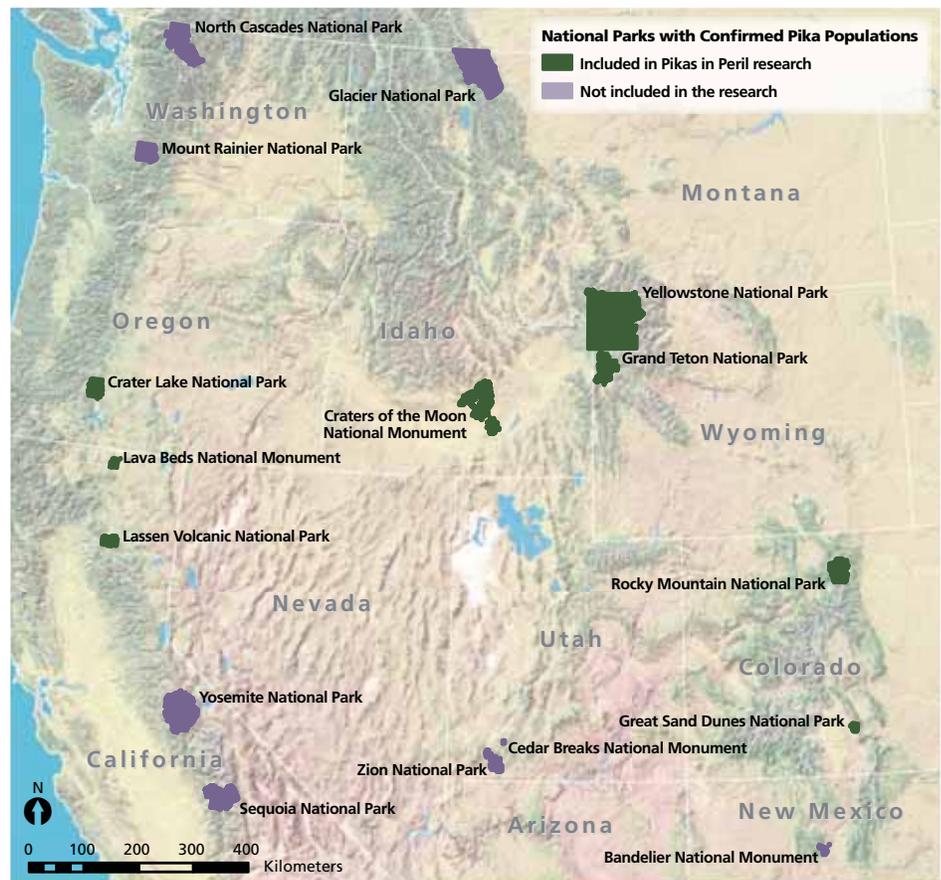
*Because of the habitat requirements and limited dispersal ability of American pikas, we expect that habitat in national parks will be of increasing importance as refugia and therefore as source populations for future colonization.*

Teton National Park (Wyoming), Great Sand Dunes National Park and Preserve (Colorado), Lassen Volcanic National Park (California), Lava Beds National Monument (California), Rocky Mountain National Park (Colorado), and Yellowstone National Park (Wyoming, Montana, and Idaho) (fig. 2). Researchers from the University of Colorado–Boulder and University of Idaho, along with park biologists and seasonal technicians, conducted occupancy surveys and collected fecal DNA in 2010 and 2011. Researchers from Oregon State University are analyzing the DNA samples to assess gene flow patterns in pika populations.

## Pikas and climate change

The American pika is considered a climate-sensitive sentinel species that faces increasing risk of extinction because of climate change in the western United States. Climate change assessments for sentinel species such as the pika give park managers insights into the expected rate and magnitude of ecological effects, and are critical for park scenario planning in the face of climate change.

Major knowledge gaps regarding expected effects of climate change on species distribution can easily be bridged for the pika, relative to other species. Pikas are ideal sentinel or indicator species for climate change because they are sensitive to temperature fluctuations, have small home ranges, and are easily detected. Their high

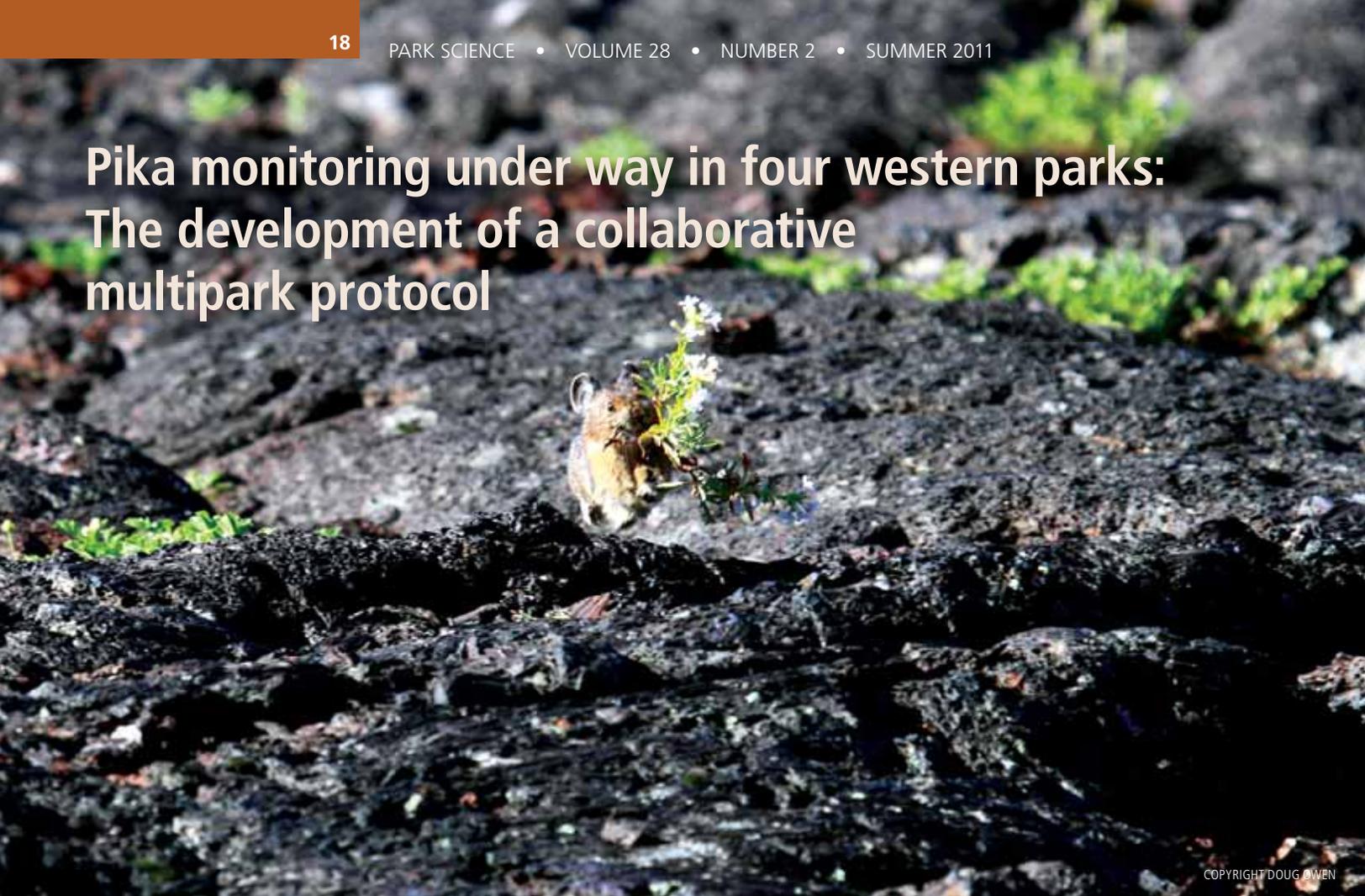


**Figure 2.** National parks with confirmed American pika populations and those being studied in the Pikas in Peril research.

visibility helps make a strong connection to visitors in national parks. Pikas must maintain their body temperature within a narrow range of only a few degrees, and a study found that when pikas are caged in the open at lower-elevation sites, extended exposure to temperatures of only 78°F (25.5°C) can be fatal (Smith 1974). Therefore, pikas tend to be restricted to boulder-strewn talus fields, often in high alpine areas and in some cases lava flows, where

abundant crevices and cavities provide sufficient cover and thermal refuge (see fig. 1) (Smith and Weston 1990). Additionally, since pikas are herbivorous and do not hibernate, they must collect and store food for winter survival. Consequently, both summer conditions (temperature) and winter conditions (snowpack) can affect their ability to survive and reproduce.

# Pika monitoring under way in four western parks: The development of a collaborative multipark protocol



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By Mackenzie Jeffress and Lisa Garrett

**RECOGNIZING THE NEED TO UNDER-**stand pika population dynamics over time, resource managers from four national parks in the Pacific West Region (Crater Lake National Park, Oregon; Craters of the Moon National Monument and Preserve, Idaho; and Lassen Volcanic National Park and Lava Beds National Monument, California) have formed a partnership with the Upper Columbia Basin Network Inventory and Monitoring Program to develop a long-term monitoring protocol for the American pika (*Ochotona princeps*) (fig. 1). Protocols produced by the Inventory and Monitoring Program follow rigorous guidelines and are expected to withstand the test of time. The objectives of the monitoring protocol are to determine current patterns and long-term trends in pika site occupancy in the four parks. These parks represent a range of habitat types, from classic high-elevation talus and boulder fields to relatively low-elevation lava flow environments (figs. 1 and 2).

## Abstract

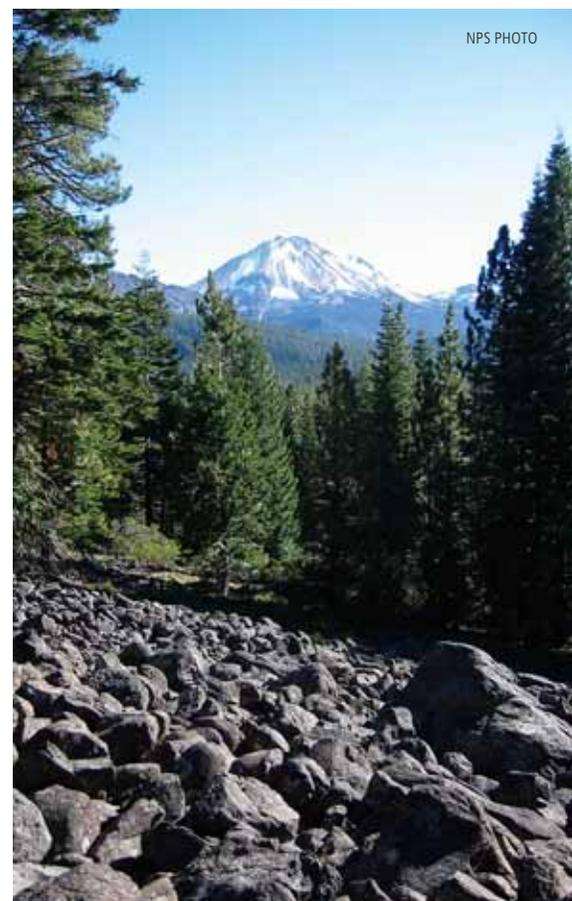
Several parks and an Inventory and Monitoring network have teamed up to develop and implement a long-term monitoring protocol for the American pika. Repeat surveys of sites to determine pika presence will be used to evaluate the status and trends in pika site occupancy patterns in four national parks.

## Key words

American pika, occupancy, *Ochotona princeps*, monitoring, status, trend

**Figure 1 (above).** Scurrying across lava at Craters of the Moon National Monument, an American pika carries flower clippings that it will use as a winter food source.

**Figure 2 (right).** The foreground rocks in this view of Table Mountain at Lassen Volcanic National Park represent high-elevation talus habitat of pika. Lassen Peak rises in the background.



NPS PHOTO

*Recent ideas focus on promoting resilience to global warming, such as protecting meadow and foraging zones adjacent to pika taluses and lava, using rock materials and designs to create pika habitat and corridor routes between occupied habitats, and using attractants to lure pikas along corridors to higher-elevation habitats.*

The approach for monitoring pika populations on national park lands is based on repeat presence-absence surveys of randomly selected, small, circular plots representing an average territory size that will permit detection of changes in site occupancy patterns over time. Sites are searched for evidence of pika presence, including sighting, and detection of calls, fresh feces, and fresh hay piles (figs. 3 and 4). Site occupancy is an efficient and informative measure of change in animal populations across broad scales (Jones 2011), and occupancy models can be used to examine factors affecting site occupancy and rates of turnover in site occupancy, such as climate and habitat characteristics. Presence-absence surveys have been successfully used to map the distribution of the species at Craters of the Moon (Rodhouse et al. 2010). The Pikas in Peril research project (see previous article) has also adopted this protocol for field surveys.

The initial focus of the protocol is to obtain additional baseline information about the distribution and occupancy of pikas in each of the four parks. As more information becomes available, the focus will shift toward trend detection, in which changes in occurrence patterns will be compared against baseline estimates for each park, and biologically meaningful declines or increases in pika occupancy can be described. Ultimately, data from this monitoring program will contribute to understanding relationships between pika site occupancy patterns and park environ-



**Figure 3.** Fresh pika feces help researchers determine if a site is occupied and are also important for genetic analysis as part of the Pikas in Peril research.

mental conditions, which will then inform park management decisions.

Not only will this protocol capture changes in the proportion of sites occupied, but also data collected by these methods can inform managers about where high-priority habitat is found and where changes in pika populations are occurring. Although tools for managing pika populations and habitat are not yet well developed, recent ideas focus on promoting resilience to global warming, such as protecting meadow and foraging zones adjacent to pika taluses and lava, using rock materials and designs to create pika habitat and corridor routes between occupied habitats, and using attractants to lure pikas along corridors to higher-elevation habitats (Hobbs et al. 2010). Since these ideas are new and have not yet been tested, our focus has been on designing a rigorous but flexible protocol that will inform park management decisions in the



**Figure 4.** Pikas pile hay in rock crevices as a winter food supply. This animal sign helps researchers determine if a site is occupied.

future as climate change response strategies are developed.

The protocol (Jeffress et al. 2011) details the why, where, how, and when of a pika monitoring program and includes specifics for selecting survey sites, training observers, and data analysis and reporting. The protocol was peer-reviewed and recently published as part of the NPS Natural Resource Report series. Pilot data were collected in all four parks in 2010 and protocol implementation began in summer 2011 with data analysis ongoing throughout fall and into winter. Given that 16 units of the National Park System contain confirmed pika populations, the protocol creates an opportunity for collaboration and regional synthesis of broad-scale trends. Other parks, as well as other agencies and groups, including several national forests and the Seventh Generation Institute, are interested in adopting the protocol. For

CONTINUED, RIGHT COLUMN, PAGE 95 >>

# Features

## Climate change science in Everglades National Park

By Carol L. Mitchell and Jerome A. Krueger

**C**LIMATE CHANGE POSES A significant challenge to National Park System units in southern Florida. Everglades National Park has long faced challenges to the preservation of its natural resources because of surrounding water management infrastructure, and is considered one of our nation's most imperiled landscapes. A majority of the park's 1.5 million acres (0.6 million ha) lies below 1 m (3 ft) of elevation and is exposed to the sea. Predictions of 21st-century climate change that include potential sea-level rise of more than 1 m (3 ft), combined with forecasted temperature increases of as much as 5°C (9°F), pose a significant predicament for the future ecological integrity of the park. The risk from sea-level rise, coupled with more than a century of disruption of the region's natural hydrology, is a significant challenge for natural resource management and ecosystem restoration efforts. In recognition of these challenges, climate change issues related to changing plant communities, soils, water quality, habitat loss, and endangered species are being addressed in the context of Everglades' research priorities and planning.

In this article we describe the park's science and resource management program and how we approach climate change-related research and monitoring, providing examples of how we use this information. We will also provide an example of a resource management project designed to increase resilience in the Cape Sable area of the park in response to sea-level rise over the next few decades.

### Abstract

Everglades National Park has long been recognized as one of our nation's most imperiled landscapes. A significant portion of the park's 1.5 million acres lies below 1 m of elevation, within projections of the rise of sea level by 2100. Coupled with the century-old disruption of the area's natural hydrology and constraints posed by adjacent urban and agricultural lands on species and habitat movement, the projected impacts from climate change are a significant challenge for both natural resource management and ecosystem restoration efforts. We have initiated, and partnered to accomplish, a wide range of monitoring, research, and simulation modeling activities to describe the current and future influence of climate change on the park. We have also implemented a resource management project designed to provide increased resilience to the Cape Sable area of the park as sea level rises over the next several decades.

### Key words

climate change research, Everglades, monitoring, resource management, sea-level rise

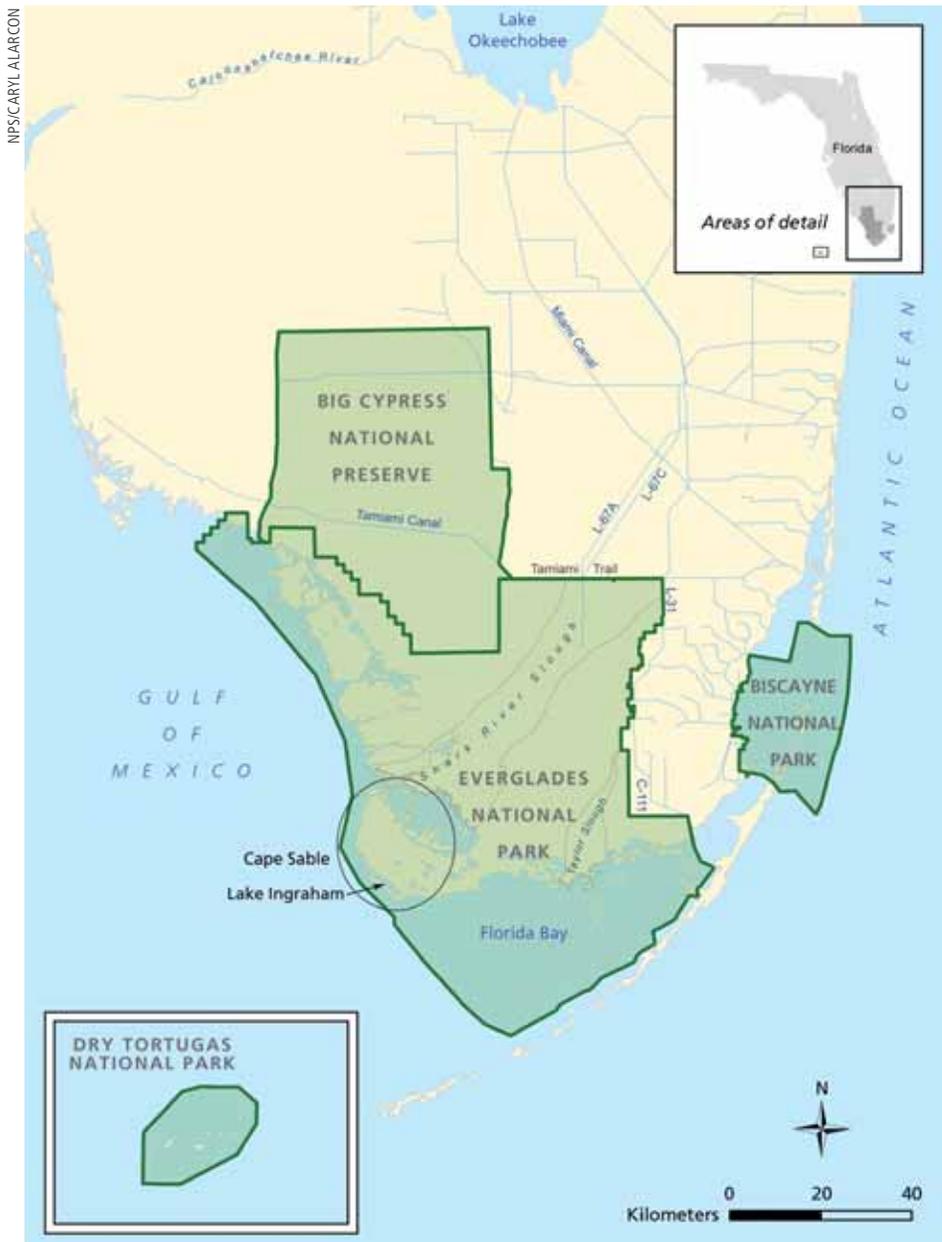
### The South Florida Natural Resources Center

The South Florida Natural Resources Center (SFNRC) is the natural resources and science arm of Everglades and Dry Tortugas National Parks, and as such is engaged in inventory, monitoring, and natural resource management activities in these two parks. In addition, the SFNRC provides science support for ecosystem restoration not only to Everglades and Dry Tortugas but also to Biscayne National Park and Big Cypress National Preserve, which neighbor Everglades to the east and north, respectively (fig. 1). The SFNRC manages the Critical Ecosystems Studies Initiative (CESI), a technical and scientific program that supports monitoring, research, computer modeling, and resource assessment activities that provide science input to on-the-ground resource managers, to the Everglades National Park superintendent, and decision makers in the U.S. Department of the Interior's (DOI) Everglades Restoration Initiative.

In 2005 the SFNRC began to incorporate climate change and sea-level rise into research and science dissemination activities ([www.nps.gov/ever/naturescience/sfnrc.htm](http://www.nps.gov/ever/naturescience/sfnrc.htm)). In 2009 the south Florida DOI agencies (National Park Service [NPS], U.S. Fish and Wildlife Service, and U.S. Geological Survey [USGS]) developed science priorities that included a request for proposals to study the effects of climate change and sea-level rise on natural resource management and ecosystem restoration in the national parks and national wildlife refuges of the region.

### Determining science needs

Climate change and sea-level rise are two of the many factors that affect natural resource management in the Everglades. Other critical resource concerns are the operation of the vast water management system that provides flood protection and water supply to south Florida residents, impacts of visitor use (particularly boating and fishing in the area of Florida Bay),



**Figure 1.** The South Florida Natural Resources Center provides science support for ecosystem restoration to four national park areas in south Florida. A major science initiative of the center is monitoring effects of sea-level rise on freshwater marsh areas of Cape Sable.

exotic invasive species, water-quality problems resulting from nutrients and contaminants, and changes to the urban and agricultural landscape along the eastern border of the park. These concerns overlie an ecosystem mosaic that includes rare and endangered species, keystone species, and critical habitat, and constitute a more immediate threat to park resources than either climate change or sea-level rise.

Nevertheless, it is clear that forecasted changes in precipitation as well as rising sea level are expected to strongly affect Everglades National Park in the future (Pearlstone et al. 2009), and that these changes will interact substantially with all the other resource threats now faced by the park. Everglades National Park requires science and analyses that will assist in decision making for natural resource management,

as well as analyses that will allow us to create and defend science-based positions and decisions regarding the interagency ecosystem restoration program in south Florida. Thus, science questions and resource management projects that match all the above categories—critical habitats or species, current threats, and future climate change—become a high priority for action in Everglades. The matching of proposed climate change science projects with current resource issues as well as with predicted climate change effects is a basic science planning strategy that may be useful to other parks facing climate change-related management challenges.

## Climate change science is contributing to natural resource management

Everglades National Park is engaged in two climate change projects that directly contribute to natural resource management.

**Cape Sable restoration.** Cape Sable is a coastal ecosystem in the extreme south-western corner of Everglades National Park, at the mouth of Shark River (figs. 1 and 2). This area was historically known as a place where freshwater marsh was separated from salt-marsh and estuarine habitats by a long, low natural feature called the “buttonwood embankment.” In the 1920s and 1930s, before the creation of the park, settlers dug a series of drainage canals through the embankment, which have grown in size and increased the loss of freshwater from the system, allowing the intrusion of tide-driven saltwater far up into the freshwater marsh habitats. The resulting collapse of the freshwater marsh upstream of the cape, and transformation to open brackish water habitat, have become more extensive over the past 30 years. Furthermore, Lake Ingraham, formerly isolated from tidal influences, has

become heavily sedimented and significantly more saline (see fig. 2).

These changes were wrought by human activities; however, the rise of sea level along the southern coast of Florida is expected to accelerate these changes in the habitats along the cape. In order to understand the effects of the canals, the CESI program funded Dr. Harold Wanless of the University of Miami to study the evolution of the canals and the rate of sedimentation into Lake Ingraham (Wanless and Vlaswinkel 2005). This study emphasized that significant change in the Cape Sable area is inevitable because of the canals, sea level, and tropical disturbances. In 2010, \$7 million in American Recovery and Reinvestment Act funding supported repair and reinstallation of plugs in two of the major canals that allowed the unnatural intrusion of saline water into the freshwater marsh (fig. 3). Though park staff realizes that over the next century these plugs may be affected by rising sea level, the project provides a higher level of safety to visitors, who commonly travel by canoe and kayak in the Cape Sable backcountry, and natural resource benefits that include redirection of tidal flows through natural channels that should enhance the resilience of the Cape Sable ecosystem during this period of change (SFNRC 2008).

Dewitt Smith, SFNRC scientist, is managing a hydrologic monitoring program upstream and downstream of the new plugs, as well as in canals that have not yet been plugged. These data will allow us to determine the effects of the plugs on salinity patterns in the freshwater marshes upstream of the buttonwood embankment. Remote imaging, available before and after canal plugging, can also provide data regarding physical changes to the upstream freshwater marshes. These sources of information should give us a sense of how the plugs may be affecting the resilience of these coastal freshwater habitats over the next decades.

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## *The relative tolerance of rare species to changes in salinity can allow managers to propose and prioritize actions needed to conserve these species.*

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**Management of rare plant species in coastal hammocks.** In 2010 a CESI project was funded to provide resource managers information about plant species of management concern in coastal habitats in Everglades National Park. Investigators Sonali Saha (Institute for Regional Conservation) and Jimi Sadle (Everglades National Park) are gathering information on plant community composition and relative abundance of species in two types of coastal hammocks, and are monitoring salinity in the soil and groundwater. Hammocks are isolated islands of trees, upland shrubs, and herbs found in the freshwater and coastal marsh habitats of the Everglades (fig. 4). These field data form a baseline for future monitoring and detection of changes in relative abundance of species as the coastal hammock ecosystems respond to increasing salinity in the soil and groundwater. In addition, these investigators are conducting experiments to determine the salinity tolerance of a select number of species.

This baseline plant inventory will be useful to resource managers in several ways. First, the relative tolerance of rare species to changes in salinity can allow managers to propose and prioritize actions needed to conserve these species. Second, the experimental and field data on salinity tolerances can be analyzed in conjunction with predicted changes in salinity that are the joint result of sea-level rise and restored freshwater flows to the coast. Such information is useful for planning ecosystem restoration—providing for the appropriate quantity of freshwater needed to support optimal soil and groundwater salinity conditions for coastal hammocks.

## **Determining freshwater needs of south Florida parks**

Climate change science is contributing to ecosystem restoration by addressing this important issue in the following ways:

**Everglades physical monitoring network.** Everglades National Park manages an extensive network of monitoring stations that record numerous variables associated with hydrology, salinity, and climate. Park science staff is able to leverage the information derived from monitoring to better understand and evaluate risk related to the response of habitats and species to factors such as sea-level rise. In this issue of *Park Science* (see page 26) Erik Stabenau and his colleagues relate their observations about measured changes in sea level in Florida Bay and the role that restoration of freshwater flows would play in counteracting saltwater intrusion in our coastal ecosystems. In essence, restoring more natural flow volumes and patterns improves ecosystem resilience in both freshwater and estuarine habitats.

**Climate change habitat suitability modeling.** Park biological resources staff is leading a collaborative effort with the USGS to develop modeling tools capable of producing robust estimates of climate change effects on the suitability of habitat for 21 species of nonmarine threatened and endangered vertebrates, such as the American crocodile (fig. 5). This effort, which includes representatives of the major federal and state agencies involved in biodiversity conservation, uses an open-code, ensemble modeling approach that



NPS PHOTO/LORI OBERHOFER

**Figure 2.** Aerial view of Cape Sable (identified by the long white beach at the left of the photo) and Lake Ingraham (tan-colored area, center), Everglades National Park, January 2011. The buttonwood embankment is visible as a pale linear feature between Lake Ingraham and the more fresh, open water habitats at the right. Work to plug one of the canals is visible in the center as four white dots.



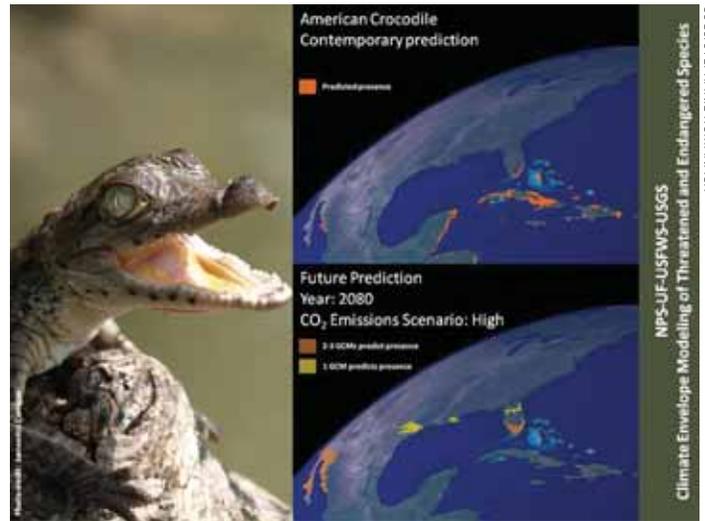
NPS PHOTO/LORI OBERHOFER

**Figure 3.** Aerial view of nearly completed dam at East Cape Canal, Cape Sable, Everglades National Park. The dams are expected to add resilience to upstream freshwater ecosystems by reducing unnatural intrusion of saltwater into the area.



SONALI SAHA, INSTITUTE FOR REGIONAL CONSERVATION

**Figure 4.** Buttonwood hammocks, named for the predominant overstory tree species, are found along the southern coast of Everglades National Park. The understory community contains several rare and endangered plant species, which are the subject of study to determine priorities for management action as sea-level rise affects groundwater and soil salinities in the hammocks.



USGS/STEPHANIE ROMANACH

**Figure 5.** Everglades National Park scientists are collaborating with the USGS to create state-of-the-art models to forecast climate change effects on threatened and endangered species in the Everglades, such as the American crocodile. Global Climate Model (GCM) predictions indicate that suitable habitat for the American crocodile will disappear from much of the Caribbean. South Florida is predicted to retain climate conditions for suitable habitat, and areas of the Gulf Coast and the western coast of Mexico are predicted to gain areas where climate conditions are suitable for development of American crocodile habitat.



**Figure 6.** Resource managers measure irradiance above a mangrove forest through the use of net radiometer and up- and down-facing quantum sensors mounted on a tower at 90 feet (27 m). Irradiance is one factor, along with atmospheric carbon and other physical factors, that influences the cycling of carbon through the mangrove ecosystem. Shark River is visible in the distance. This tower is associated with the project to measure carbon dynamics in mangrove forest.

maximizes the utility of the product by making it easily modifiable and transferable to other groups involved in conservation decision making. The goal is to understand how climate change will affect distribution of these species and allow managers to understand shifting habitat availability and needs (NPS, Everglades National Park, L. Pearlstine, landscape ecologist, personal communication, 15 July 2011).

**Measurements of carbon dynamics in mangrove forest.** An understanding of carbon dynamics of an ecosystem is essential for determining how climate change can alter existing plant communities. The mangrove forests of Everglades National Park are experiencing rapid environmental changes associated with upstream water management practices, fluctuating salinity gradients, sea-level rise, and natural disturbances such as hurricanes. SFNRC scientists Vic Engel and Jordan Barr are

working with several research cooperators using a meteorological tower and on-the-ground methods to describe carbon cycling in the mangroves and determine how at risk the mangrove habitat is from the combined effects of these disturbance variables (fig. 6) (Barr et al. 2009). This tower is part of a national network of carbon flux sites that share data and resources to understand the role of terrestrial ecosystems in climate change (<http://public.ornl.gov/ameriflux>). The work in quantifying carbon flux in Everglades mangroves will help to shape future NPS positions regarding the amount of freshwater needed for ecosystem restoration.

**Hydrologic modeling and modeling of Florida Bay.** Everglades National Park and other agencies involved in south Florida ecosystem restoration rely on hydrologic and other models of the physical system to assess effects of proposed restoration actions. Although these models

were developed primarily to determine the effects of changes to the quantity and timing of upstream freshwater flow, there has also been a need to determine how proposed changes in freshwater flow affect salinity patterns in estuaries such as Florida Bay. The CESI program has funded several projects to link upstream freshwater models with coastal salinities (Nuttall 2002; Marshall 2009). These models allow evaluation of effects of upstream flow conditions on coastal salinities; however, they are not designed to capture how downstream change (i.e., sea-level rise) would affect estuaries. New analyses are needed that allow integration of the effects of both upstream flow conditions and sea-level rise on salinities in Florida Bay and other coastal habitats in Everglades, such as the Cape Sable area.

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*Forecasted changes in precipitation as well as rising sea level are expected to strongly affect Everglades National Park in the future . . . these changes will interact substantially with all the other resource threats now faced by the park.*

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## Future climate change research efforts

While SFNRC staff has participated in numerous successful climate change science efforts, significant challenges remain. It is vital to expand our efforts to understand the expected magnitude of climate change effects on the Everglades and its natural resources. We will also need to retain and adapt our hydrologic and ecological monitoring networks to the coastal environment as it advances landward. We need to gain an understanding of the interaction between forecasted climate change and invasive species to adapt our management, control, and containment of these species. Like parks in other areas, south Florida parks require reliable local physical climate change models, specific to the Everglades region, to improve our understanding of the interaction of upstream freshwater flows with sea-level rise along the coast. These local models, downscaled from the suite of accepted global climate models, will help us make informed decisions regarding not only resource management but also proposals for infrastructure or changes to visitor use of different park areas.

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# Sea-level rise: Observations, impacts, and proactive measures in Everglades National Park

By Erik Stabenau, Vic Engel, Jimi Sadle, and Leonard Pearlstine

**T**HE FLAT EXPANSE OF SAWGRASS marsh and mangrove coastline in Everglades National Park, Florida, serves as valuable habitat for a number of unique, rare, or endangered species. Unfortunately, this same expanse, with only about a 5 cm (2 in) increase in elevation per linear kilometer (0.6 mi) inland, makes the region exceptionally vulnerable to the effects of sea-level rise. Slight increases in sea level are expected to lead to disproportionate increases in inundation periods for broad areas in the park, and have already influenced both surface and subsurface saltwater intrusion. Saltwater intrusion has also likely been influenced by reductions in freshwater discharge that have accompanied upstream development over the past century. These hydrologic changes put pressure on the ecosystem, causing a variety of impacts, such as inland migration of plants, variation in species composition, and disruptions of predator-prey relationships (Pearlstine et al. 2010). Salt-tolerant mangrove species have already migrated approximately 3 km (2 mi) inland since the 1940s in parts of the national park, presumably in response to rising sea level (Ross et al. 2000).

Understanding these impacts and protecting park resources are critical when one considers that only 10% of all coastal areas that are below 1 m (3 ft) elevation in the eastern United States have been set aside for conservation (Titus et al. 2009). Many coastal resources in Everglades National Park are not protected elsewhere in the United States. Faced with these challenges, our group is examining the factors that regulate variability in the long-term record of sea level maintained at Key West, Florida, located less than 100 km (62 mi) south of the park's southernmost land-

**Abstract**  
Everglades National Park, because of its flat landscape, is particularly vulnerable to the impacts of sea-level rise. The goal of the Comprehensive Everglades Restoration Plan is to improve the quantity, quality, timing, and distribution of freshwater to the greater Everglades region, primarily for habitat restoration purposes, yet this program may also provide reprieve from an adverse impact of sea-level rise: saltwater intrusion. We present here evidence that sea-level rise and saltwater intrusion are affecting the park with changes evident in the composition of coastal forest communities. Controlled experiments reveal species-based differences in the salinity tolerance of plants in the coastal community and suggest that climate change may alter the coastal ecology of the park. Furthermore, in some regions a common response to saltwater intrusion, upland migration, is not likely because of a lack of suitable habitat and, as a result, local ecological changes are probable. Park management is developing prioritized protection options for species and habitats at risk in light of climate change.

**Key words:** climate change, restoration, saltwater intrusion, sea-level rise, water management

ward extent. We are also investigating how freshwater management strategies and rainfall fluctuations interact with rising sea level to influence water and salinity levels and plant community composition in the park's coastal wetlands. This information should eventually assist in determining the potential ecological consequences of rising sea levels in the park's most vulnerable habitats.

## Sea-level rise and water management

Surface water stage (elevation relative to a fixed datum) in the coastal wetlands of the park is determined by the interaction between tidal influences and the quantity of freshwater released through water management structures across the park's upstream boundaries. Freshwater flows through Shark and Taylor sloughs, two wide, shallow, slow-moving expanses of surface water that are the primary drainage features of the park. An extensive set

of hydrologic monitoring stations in these sloughs provides continuous data on rain, temperature, salinity, and surface water stage. Initially we used this data set to determine the rate of change in stage for the stations in the freshwater-to-marine transition zones of Shark and Taylor sloughs (fig. 1). The results from station P35 are provided as an example of this work (fig. 2). For this station we calculate, using least-squares regression, an increasing linear trend in water levels of 2.61 mm/yr (0.1 in/yr) from 1952 through 2010. This rate is higher than the average global rate of sea-level rise of 1.7 mm/yr (0.07 in/yr) from 1961 to 2003, but not significantly different from the recent satellite-based estimate of  $3.1 \pm 0.7$  mm/yr ( $0.12 \pm 0.03$  in/yr) for 1993–2003 (Bindoff et al. 2007). It is also in agreement with the rate of 2.36 mm/yr (0.09 in/yr) observed at Key West, Florida, over the past 110 years, which totaled 0.26 m (10.2 in).

The long-term, linear trends in average water levels observed at Key West and P35

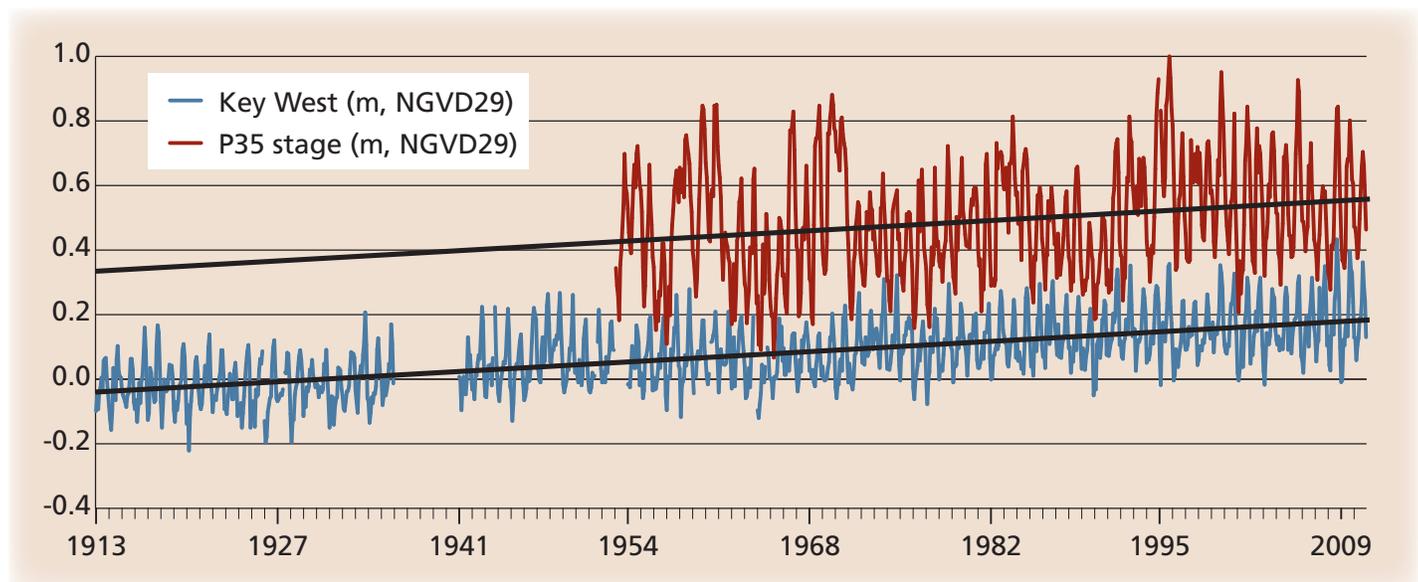


**Figure 1.** Map of Everglades National Park showing the location of hydrologic monitoring stations, water control structures, and other key features. The buttonwood embankment along the southeastern edge of the mainland portion of the park, isolated between Florida Bay and inland lakes, is highlighted in purple and shown with arrows.

(see map) represent only one aspect of how changing water levels along the coast may affect park resources. Significant interannual to (multi)decadal-scale variability in the rate and magnitude of change in water levels is also observed in these two records. Wavelet analysis, a technique that reveals the time period of cyclical events in a data time-series, was used to evaluate relationships between changes in water levels in or near the park and global cyclical climate features. This analysis revealed that sea level at Key West and marsh water levels at station P35 both vary on frequencies that correlate with shifts in the North Atlantic Oscillation (NAO) and the El Niño Southern Oscillation (ENSO). These oscillations are indicators of changes in global circulation patterns, contain both atmospheric and oceanic components, and are related to ocean temperatures and variations in ocean currents. Results of the wavelet analysis suggest that sea levels around southern Florida and precipitation on the Florida peninsula are influenced by large-scale climatic processes, and that any changes in sea level because of these factors may in turn affect coastal marsh water levels and salinity values through direct hydrologic connections. The

physical basis of the relationships among NAO, ENSO, and Key West water levels is uncertain at this point, but it is thought to be related to changes in the rate of flow in the Florida Current or to temperature-related changes, where thermal expansion or contraction of surface water causes changes in sea-level in the Caribbean Sea (DiNezio et al. 2009). The NAO and ENSO may also affect marsh water levels directly by influencing precipitation timing and amounts (Kwon et al. 2006; Abtew and Trimble 2010). Because of the independent and cyclical nature of these climate features, there are periods during which their influences combine to cause short-term increases in water levels that are significantly faster than the long-term trend (Engel et al. 2010). For example, the periods 1965–1971 and 1988–1995 were marked by an accelerated rise in both sea and marsh water levels compared with long-term trends.

Water released through the hydrologic control structures along the northern boundary of Everglades National Park discharges through the coastal marshes into Florida Bay and the Gulf of Mexico. Upstream water management practices



**Figure 2.** Station P35 water-level time series (red) with linear trend (black) showing that the rate of marsh water-level rise is similar to the rate of sea-level rise observed at the Key West tide monitoring station (blue).

may affect coastal marsh water levels, the location of the freshwater-saltwater interface, and estuarine salinity values. The amount of water released to the park is generally dependent on prevailing rainfall amounts and the resultant water levels in the water conservation areas adjacent to the northern boundary of the park, but is also regulated by other factors, including concerns over impacts on endangered species (Lockwood et al. 2001). The U.S. Army Corps of Engineers and the South Florida Water Management District regulate the water releases to the park based on recommendations from the region's stakeholders, including the National Park Service and other federal (e.g., U.S. Fish and Wildlife Service), state, local, and tribal organizations.

In the future the Comprehensive Everglades Restoration Plan, which guides the multiagency restoration effort for the greater Everglades ecosystem, is intended to restore the historical quantity, quality, timing, and distribution of freshwater flows. It is not yet known how enactment of this plan will affect current trends in coastal wetland water levels and the rate of saltwater intrusion into Everglades National Park. Sea level has already increased substantially since drainage activities on the mainland began in the late 1800s. The restoration of freshwater flows toward pre-drainage conditions will likely increase marsh water levels and reduce the extent of saltwater intrusion caused by changing sea levels and past management practices. However, the combined impacts of higher freshwater inflows and further increases in sea level on the park's coastal ecosystems are unknown. Both the magnitude and the rates of change in hydrologic conditions as influenced by climate factors will determine ecological outcomes in this region.

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## *Determining the ecological tolerances of tree species is essential to understanding how community changes will occur, given the expected changes in sea-level rise.*

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### **Ecological consequences for imperiled habitats**

Expansive freshwater wetlands gradually intergrade or mix with saline marshes and mangrove forests at the southern tip of Florida in Everglades National Park. A slightly elevated embankment, 65–100 cm (26–39 in) above current mean sea level, lies just north of the open saline waters of Florida Bay, between Cape Sable and Joe Bay (fig. 3). This narrow ridge is bordered on the north and south by tidally influenced salt marsh and mangrove forest. The elevation prevents tidal and seasonal flooding and the soils of this formation hold a freshwater lens generated by rainfall (Olmsted and Loope n.d.). Buttonwood (*Conocarpus erectus*) trees form a relatively open-canopy forest along the lower slopes of the embankment (65–85 cm [26–33 in]) while tropical hardwood trees, including mahogany (*Swietenia mahogany*), Jamaica dogwood (*Piscidia piscipula*), and Spanish stopper (*Eugenia foetida*), form closed-canopy forests at the highest elevations (85–100 cm [33–39 in]). A number of rare plant species not found elsewhere in the United States, including orchids, cacti, herbs, and shrubs, live in these forest communities. Because of its restricted size, low elevation, proximity to the coast, and lack of similar geologic features nearby, these plant communities are considered to be particularly vulnerable to the effects of sea-level rise. The distribution of other plant community types in relation to salinity suggests that an increase in mean sea level of as little as 20 cm (8 in) will result in a transformation of the buttonwood forest to a herbaceous salt marsh or mangrove

forest. With this change, buttonwood trees will move upslope to replace the tropical hardwood hammock. These community changes will be coupled with impacts on already imperiled subcanopy species. For example, Cape Sable thoroughwort (*Chromolaena frustrata*) is an endemic terrestrial herb that lives in the ecotone between buttonwood and tropical hardwood forests. Its tolerance to soil salinity will determine its ability to persist in this changing environment. In addition, Cape Sable thoroughwort appears to rely on the shady conditions created by the overstory of buttonwood and tropical hardwood trees. Thus its survival is linked to the persistence of this forest complex.

Increases in groundwater salinity within the buttonwood embankment are expected to precede actual inundation with ocean water as sea level rises. This will likely have differential impacts on plant species that occur in coastal hammocks. Determining the ecological tolerances of tree species is essential to understanding how community changes will occur, given the expected changes in sea-level rise. In addition, monitoring changes in groundwater salinity and changes in the frequency and extent of flooding events will help improve our estimates of the rate of environmental changes. Finally, understanding the impacts of these changes on plant species of management concern will allow us to prioritize management actions. Everglades National Park, in cooperation with the Institute for Regional Conservation, is using greenhouse experiments to determine the salinity tolerance of species integral to hammock structure as well



NPS/JIMI SADLE

**Figure 3.** A coastal hammock and buttonwood forest winds along the north shore of Florida Bay. These higher-elevation communities are flanked by salt marsh, mangrove, and open-water communities, preventing migration of plant species as sea level rises.

as rare plant species that occur among coastal hammock vegetation. We installed a network of groundwater monitoring wells within the communities found on the buttonwood embankment. Using a survey-grade global positioning system, we will obtain precise elevation profiles of habitats and rare plant populations found throughout the buttonwood embankment. Finally, using isotopic analysis of stem and soil water, we will determine where in the soil horizon key plant species are obtaining water.

Our initial results indicate species along the coast have variable tolerances to salinity. Two important structural components of tropical hardwood hammocks, West

Indian mahogany and Jamaica dogwood, showed greater reduction in relative growth rates and leaf gas exchange in high-salinity (15 and 30 parts per thousand [ppt]) treatments than did Spanish stopper and buttonwood. In addition, mortality was significantly greater in one-year-old juveniles of Jamaica dogwood than in all other species in high-salinity treatment as opposed to low-salinity (5 ppt) and control treatments. These results may provide clues to the mechanism causing coastal hammock collapse first described in the early 1980s (Olmsted et al. 1981), in which significant losses of Jamaica dogwood trees were reported but the cause was not determined.

According to Intergovernmental Panel on Climate Change estimates, which are considered conservative, the sea-level rise we are already experiencing in southern Florida may exceed 20 cm (8 in) in the next 30–40 years. Under this scenario we might expect catastrophic changes in these important habitats in the next few decades. However, the fate of these plant communities can be altered by both natural processes and human intervention. Soil deposition events from periodic hurricane storm surges have increased the elevation of coastal embankments in the past (Whelan et al. 2009; Davis et al. 2004). While these deposition events are expected to provide a measure of resistance to rising sea level, they are also a source of

saltwater inundation. Increases in freshwater flows through restoration efforts may offset increases in soil salinity in the coastal habitats.

Continuing efforts will be focused on quantifying the effects of increased freshwater delivery on the rate of change in saltwater intrusion and the resultant ability of the coastal system to migrate or adapt. In certain cases, where adverse impacts are inevitable and can be clearly identified, proactive measures, such as seed banking or maintenance of *ex situ* populations of imperiled plant species, may be warranted.

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# Landscape response to climate change and its role in infrastructure protection and management at Mount Rainier National Park

By Scott R. Beason, Paul M. Kennard, Tim B. Abbe, and Laura C. Walkup

**I**N NOVEMBER 2006 AN INTENSE storm dropped 45 cm (17.9 in) of rain over 36 hours at Mount Rainier National Park, Washington. The record floods from this event caused the park to be closed for six months, destroying roads and trails, damaging utilities, and cutting off access to park campgrounds. The region overall has seen increasing flood damage: six of the largest storms on record have occurred in the last 25 years (Parzybok et al. 2009). Flooding at Mount Rainier is not uncommon, but the November 2006 flood was by far the most destructive in park history and its effects are still felt today. Though one might conclude that the 2006 flood was an anomalous event in the park's history, recent trends in flooding, aggradation (excessive sediment accumulation in riverbeds), debris flows, glacial recession, and warming temperatures are consistent with effects of climate change.

Because of steep topography, Mount Rainier hosts significant development in valley bottoms near rivers. Large portions of the mountain's infrastructure are built in the rustic style of architecture from the early 1900s, and make up the park's designated National Historic Landmark District (NHLD), the highest level of cultural resource protection. Much of this development occurred before recognition of hazards associated with building near rivers. For example, the Carbon River Road on the northwest side of the park was built along the grade of the river. Repeated flooding in the 1990s and subsequent destructive floods in 2006 and 2008 have

## Abstract

Mount Rainier is a 4,392 m (14,410 ft) volcano that presents considerable risks from numerous natural hazards. While most of the spectacular hazards associated with volcanoes happen infrequently and are usually preceded by warning signs, flooding and debris flows occur more often and sometimes without warning. Devastating floods at Mount Rainier National Park, Washington, have increased in frequency in the last decade and have led to tens of millions of dollars' worth of damage to park infrastructure. Major rivers at Mount Rainier are fed by glaciers and are aggrading, or filling in with sediment, at rates of up to 1.8 m (6 ft) per decade whereas historically they were aggrading at 7–13 cm (3–5 in) per decade. As a consequence of regional climate warming, all of the 25 glaciers in the park are retreating and thinning; as glaciers retreat, unconsolidated and unstable sediment is exposed and mobilized into rivers, which causes aggradation downstream. This tremendous increase in aggradation is filling in stream channels and enlarging floodplains, which leads to more frequent catastrophic shifts (avulsions) in the location of river channels. Avulsions tend to destroy park infrastructure and disturb riparian forest habitat. Future climate warming scenarios published by the University of Washington's Climate Impacts Group anticipate increased year-round temperatures with no significant change in yearly precipitation. These factors favor glacial retreat, decreased snowpack, increased debris flows, and a much larger variation in the occurrence and magnitude of regional flooding. For infrastructure management and planning, protection of natural resources, appreciation of riparian processes, and overall employee and visitor safety, we need to understand the changing river hydraulics because of excess sediment supply and its ties to climate change.

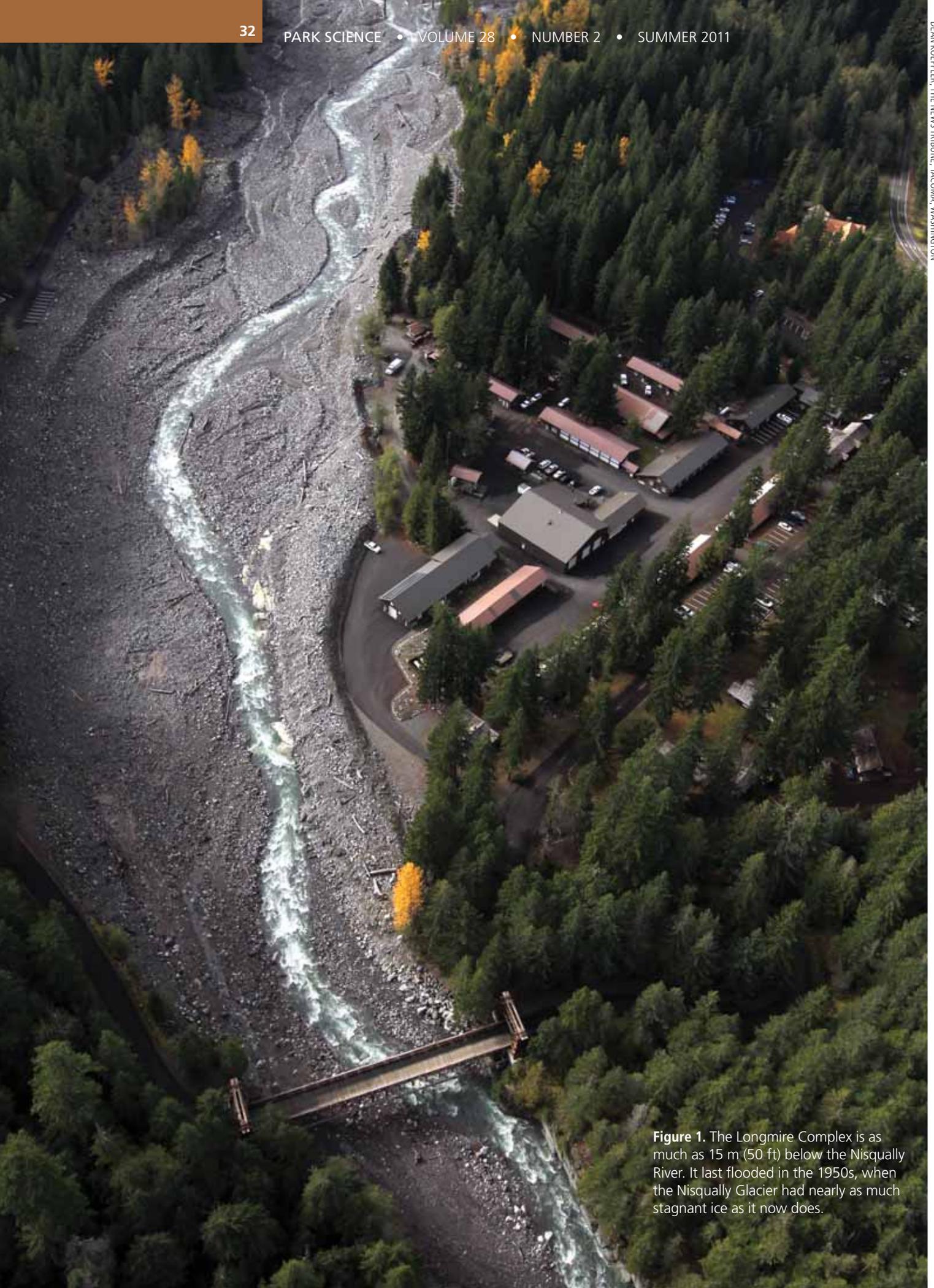
## Key words

aggradation, climate change, debris flows, floods, glacial retreat, rivers

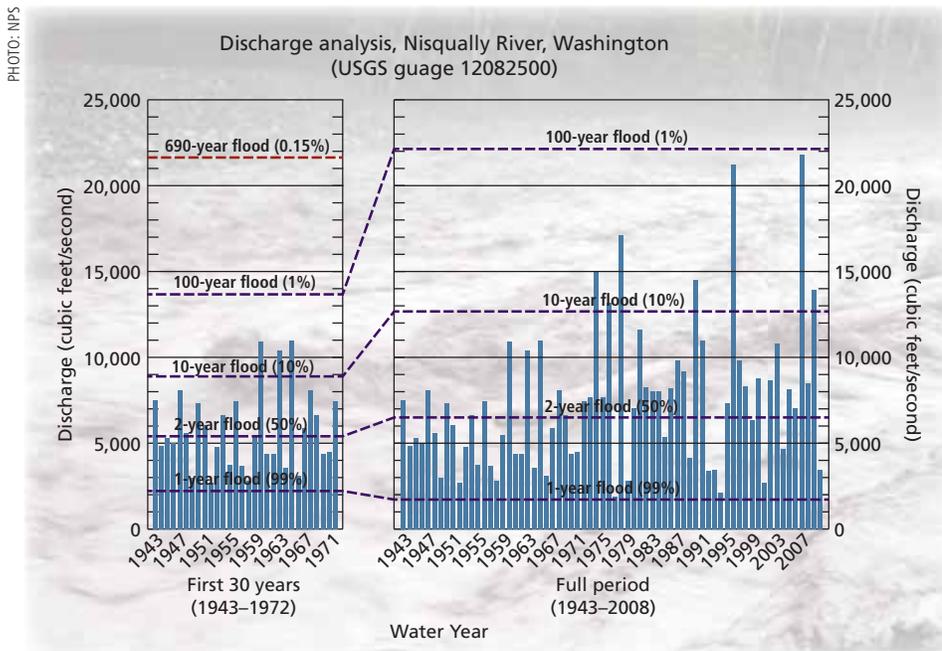
damaged significant portions of the road, cutting off access to the northwestern portion of the park. The Longmire Complex, which is one of the main developed areas on the west side of the park, is located adjacent to the Nisqually River. This river is up to 30 feet in elevation higher than nearby roads and park buildings, which are only protected by a small levee (fig. 1, next page). Park staff must determine how best to manage infrastructure in peril, including areas that have been designated as NHLD features.

## A changing landscape

Steep moraines and debris-rich glaciers continually provide sediment to Mount Rainier's rivers, causing them to develop into an intricate system of complex braided channels. The riverbeds, on average, are rising by natural sedimentation and aggradation processes. For the same-size storms, the flood potential is ever increasing since the capacity of the river channels is reduced as they fill in with sediment (Beason 2007; Riedel 1997).



**Figure 1.** The Longmire Complex is as much as 15 m (50 ft) below the Nisqually River. It last flooded in the 1950s, when the Nisqually Glacier had nearly as much stagnant ice as it now does.



*The 100-year event in 1972 now has a recurrence interval closer to that of a 12-year event.*

**Figure 2.** Analysis of a stream gauge outside the park shows an increase in magnitude of peak flows and a decrease in magnitude of low flows, consistent with models of regional climate change.

Park rivers aggraded, on average, 0.3 m (12 in) per decade from 1997 to 2006. The rate has increased recently to an average of 1.4 m (57 in) per decade on the Nisqually River from 2005 to 2010—and, following debris flow deposition, up to 1.8 m (6 ft) in a single event (Beason 2007).

Climate models run by the University of Washington's Climate Impact Group indicate that more winter precipitation will fall as rain rather than snow by 2100. In mid-elevation ranges, this change will result in less snow accumulation, higher winter and lower summer streamflows, earlier snowmelt, and earlier peak streamflow (Hamlet et al. 2010; Snover et al. 2003). Understanding variability in climate and the effects on river hydrology is extremely important for assessing future conditions for parks.

Recent findings concerning rivers at Mount Rainier support predictions of changing precipitation patterns and hydrology. Rainfall events exceeding 8 cm (3 in) in 24 hours had an additional 2.5 cm (1 in) of precipitation between 1976 and

2006 (Abbe et al. 2008). The magnitude of the 100-year flood has also changed. For example, on the Nisqually River, these levels have increased from 387 m<sup>3</sup>/s (13,670 ft<sup>3</sup>/s) in 1972 to 626 m<sup>3</sup>/s (22,111 ft<sup>3</sup>/s) in 2009 (fig. 2). Stated another way, a flood of 387 m<sup>3</sup>/s (13,670 ft<sup>3</sup>/s) had a 1% probability of occurring in the past, but now has an 8% chance of occurring. The 100-year event in 1972 now has a recurrence interval closer to that of a 12-year event. This increase in peak flows challenges the ability to understand and reliably predict the frequency and magnitude of large floods.

## Glacier dynamics

Major rivers at Mount Rainier National Park are glacier-sourced, and pro-glacial valleys (valleys previously carved out by the glaciers when they were advancing) control their forms and patterns. Glaciers are a critical natural resource at Mount Rainier and an important vital sign for biophysical monitoring in the North Coast and Cascades Network. Mount Rainier

has more glacial ice in its 25 named glaciers and innumerable perennial snowfields than any other peak in the contiguous United States—more, in fact, than all the other Cascade Range volcanoes combined.

Studies of glaciers on Mount Rainier have shown an overall decrease in volume. Total ice volume was estimated to be 5.62 km<sup>3</sup> (1.35 mi<sup>3</sup>) in 1913 and to have decreased by 22.7% (to 4.34 km<sup>3</sup> or 1.04 mi<sup>3</sup>) by 1971, at a loss of 0.39% per year (Nylen 2001). In 1981, the total glacier volume was measured at 4.42 km<sup>3</sup> (1.06 mi<sup>3</sup>) (Driedger and Kennard 1986). From 1971 to 1994, the rate of glacial volume loss decreased, averaging 0.13% per year with a 3.1% loss during that interval (Nylen 2001). However, Sisson et al. (2011) estimated 14% glacial ice loss between 1970 and 2008, an average of 0.37% per year, which indicates that the rate of loss sped up considerably between 1994 and 2008. Glacier volume in 2008 was estimated at approximately 3.82 km<sup>3</sup> (0.92 mi<sup>3</sup>) (Sisson et al. 2011). The rate of glacier loss appears to have shot up in recent years: new surveys on several glaciers on Mount

Rainier indicate that total glacial volume has potentially decreased by as much as 18% from 2003 to 2009 at an average rate of 3% per year, almost 10 times any of the historical rates (NPS, J. Riedel, geologist, personal communication, 1 March 2009).

Since 1931, surveys of the lower Nisqually Glacier have been conducted to determine changes in elevation of the ice surface, making it one of the longest-running glacier monitoring programs in the Western Hemisphere. These surveys show how the Nisqually responds to changes in snow accumulation. When higher-than-normal snowfall builds up in the accumulation zone of the glacier, a bulge forms, which can be tracked moving down the glacier. These bulges, called kinematic waves, can exceed 24 m (80 ft) in height, and move down-glacier at speeds up to six times faster than the ice itself. When the wave reaches the terminus, the glacier usually advances dramatically. Four kinematic waves have been observed since the project began, three of which have resulted in glacier advances. The fourth wave, expected to reach the terminus in 2005, was accompanied by glacial retreat as glacial melt overwhelmed ice advance.

There are also concerns about stagnating ice on Mount Rainier. Average ice velocities on the Nisqually Glacier were previously measured at approximately 200 mm/day (8 in) (Hodge 1974). However, recent measurements by park staff show the movement is more like 200 mm *per year* (NPS, S. Lofgren, lead climbing ranger, personal communication, 3 November 2009). Debris-rich stagnant glacier ice has been linked to destructive glacier outburst floods at Mount Rainier in the past (Walder and Driedger 1994).

Glacier loss is also linked to increased sediment availability, destructive debris flows, and outburst floods. Debris flows are fast-moving liquefied landslides of soil, rocks, trees, and anything else in their paths.

Mount Rainier has recently experienced many debris flows, and increases are predicted as glaciers continue their rapid retreat. Since 2001, there have been at least six debris flows in three watersheds that have not had such flows since the park was founded more than a century ago. During the 2005 and 2006 floods alone, 10 debris flows occurred in two days, resulting in extensive infrastructure damage. All debris flows began in areas that were deglaciated since 1913 (Copeland 2009).

Debris flow statistics alone do not prove a recent increase in debris flow frequency; the record is incomplete. Coupled with extreme landscape response (fig. 3), however, the record strongly suggests an increase. Future research will use dendrochronology to extend the debris flow record and reveal whether debris flow frequency has increased as suspected. Most recent debris flows have occurred in warm autumn storms, when perennial snow cover is minimal or absent—a condition future climate change is expected to produce more frequently.

## Hazards

Sediment mobilized by debris flows is transported to lower-gradient river valleys. The sheer volume of material in a debris flow can overwhelm the river's transport capacity and choke off a river valley, causing it to accumulate a vast amount of sediment. For example, the confluence of the Nisqually River and Van Trump Creek has aggraded 11 m (36 ft) since 1910 because of debris flow activity (Beason 2007).

Decreased glacial volume and area may lead to increasing sediment supply from steep, unstable moraines. Ground that was previously overtopped with glacial ice in steep portions of the mountain provides a readily available sediment source for debris flows; this is occurring in the vicinity of the Van Trump Glaciers and has

been the source of repeated debris flows (Copeland 2009). Additionally, periglacial ice (ice near glacial margins) may act as a structural support for loose debris, and as permafrost and periglacial ice sources are lost, so too is this support. All these mechanisms will likely lead to increasing sediment production. In turn, more sediment will be provided to already choked river channels. Over time the conveyance capacity, or amount of water a channel can transport (or carry), will decrease. Therefore, for the same-size floods, the inundated area of the floodplain will increase and may affect riparian habitat and historical infrastructure. Floodplains are also threatened by the prospect of warmer and more intense storms, which could dramatically change river hydrology. Avulsions, or rapid migrations of a river channel from its previous course, will be more likely and have been documented on the White River and Tahoma Creek (Cardno ENTRIX 2010; Walder and Driedger 1994).

## An uncertain future

Mount Rainier is a dynamic geologic landscape experiencing major changes; these changes are consistent with and likely to increase in response to regional climate change. Management complexities and knowledge gained by scientists at Mount Rainier can be applied to other places in the world. While it is impossible to control natural forces, significant progress is being made in understanding these phenomena. National Park Service scientists, along with researchers from Oregon State University, Portland State University, the University of Washington, and the U.S. Geological Survey, are scrutinizing the in-park and downstream response of the landscape and what it means for the future. Such studies suggest that aggradation is occurring in and causing problems for rivers emanating from the mountain; evidence is that these issues are not confined to the park boundary (Czuba et al. 2010). Results from current

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**Figure 3.** A surfeit of sediment due to debris flows and glacial outburst floods from the South Tahoma Glacier has led to a disequilibrium whereby Tahoma Creek has built itself up higher than surrounding land, catastrophically avulsing into an old-growth forest, which has destroyed riparian habitat and park infrastructure.

and future studies will add to a growing body of science that investigates landscape response to climate change and its role in management of resources and overall visitor and employee protection.

Mountains and rivers are dynamic systems, and their change is natural. The violent, volatile events brought on by climate change, however, pose a wide variety of serious challenges to ecosystems and infrastructure. Protecting infrastructure often results in the trade-off of damaging ecosystem components, functions, and processes. Over time, agencies charged with overseeing natural places, landscapes, and wildlife will need to evolve and adapt to these drastic and sweeping changes.

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NPS/GUY ADEMA

## Glacier trends and response to climate in Denali National Park and Preserve

By Rob Burrows, Samuel Herreid, Guy Adema, Anthony Arendt, and Chris Larsen

**G**LACIERS ARE A SIGNIFICANT resource of mountain ranges in Alaska and a dominant feature on Mount McKinley. The glaciers of Denali National Park and Preserve, Alaska, are vast, covering 3,779 km<sup>2</sup> (1,459 mi<sup>2</sup>), approximately one-sixth of the park's area. Each year, these glaciers gain mass whenever snowfall accumulates at the surface, and they lose mass primarily through surface melting (ablation) during the summer. A glacier's mass balance is the difference between accumulation and ablation and describes the overall health of the glacier. Generally, the average summer season temperature (May to September) drives total ablation for any given year and total winter snowfall drives accumulation. When deviating mass balance trends persist for many years they can result in significant landscape changes that can al-

ter park visitors' experience. These trends have a direct influence on a wide range of hydrologic, ecologic, and geologic systems. For example, glaciers provide a steady base flow of freshwater discharge upon which many ecosystems thrive, and when glacier meltwater and sediment discharge change because of a change in mass balance, these ecosystems are altered. Glaciers also advance and retreat in response to changes in mass balance, which can create new or destroy existing habitat and contribute to changes in the climate of alpine regions. Glacier behavior has a large influence on the braided river systems that are a common feature of the mountain landscapes of Alaska. On a global scale, long-term trends in glacier mass balance can make significant contributions to changes in sea level.

**Figure 1.** Researcher Adam Bucki records data from test pits and an ablation stake at the index measurement site on Kahiltna Glacier.

Each of the world's glaciers is a unique entity and has a different set of physical characteristics that dictate how it responds to changes in mass balance and hence climate. Corresponding to the wide variety of mountain shapes and sizes in the Alaska Range is a large array of shapes, sizes, and behaviors among glaciers (Molnia 2008). Important characteristics that determine glacier behavior include size, elevation range, aspect, slope, number and arrangement of tributaries, the area-altitude distribution (hypsometry), and the underlying and surrounding geology of the glacier's basin. Areas with readily erodable bedrock tend to have large areas of surface ice covered by rock debris, which can insulate the ice on the lower glacier, retarding melt rates, changing flow rates, and masking areal retreat. Many glaciers in the Alaska Range exhibit surge-type behavior, which

### Abstract

Glaciers cover approximately one-sixth of Denali National Park and Preserve in Alaska. They are not only enjoyed by visitors for their scenic and recreational values but are also an important driver of Denali's diverse ecosystems by defining the hydrologic regime, generating landscape-scale braided river systems, and shaping the landforms of the Alaska Range. Scientists from the National Park Service and University of Alaska–Fairbanks have been researching glacier dynamics and monitoring glacier trends for more than 20 years using glacier outlining from satellite imagery, index mass balance measurements, longitudinal elevation profiles, repeat photography, analysis of regional gravity changes, and other localized research. Mass balance measurements on the Traleika and Kahiltna glaciers showed a cumulative net gain of mass from 1991 to 2003. Since 2003 the mass balance data and satellite-based gravimetric analysis show a net loss of ice mass. Airborne laser and lidar elevation profiles corroborate the mass balance measurements and also show localized changes because of glacier dynamics. Analysis of glacier extent reveals an 8% loss in area since 1950; however, whereas most glaciers lost area, a few surge-type glaciers gained area. Repeated photographs from historical images help refine trends seen in other methods and include dramatic examples of smaller glaciers decreasing in size and a surge-type glacier that has not changed as noticeably. Relations to climate trends are complicated and clearly demonstrate the importance of local influences on glacier behavior and trends. Losses of ice from smaller glaciers and dramatic changes of other glaciers in Alaska suggest that global climatic change may be overwhelming the dominant influence of large-scale climate oscillations on glacier change in Denali.

### Key words

climate change, Denali, glacier, Kahiltna Glacier, mass balance, Traleika Glacier

is a periodic acceleration of all or part of the glacier to speeds of 10 to 100 times the normal quiescent speed. Surge-type glaciers may advance in a seemingly unpredictable way when other glaciers are retreating. With such a variety of glaciers it is imperative to have a thorough characterization of the glacier population and of which glaciers can represent the population as study glaciers.

The National Park Service has monitored the mass balance of two glaciers in Denali National Park since 1991. These field measurements give detailed information on mass variations at specific locations, but they have limited spatial coverage. Recently, satellite and airborne technologies have begun to provide information on glacier variations that span broader geographic regions. This article presents long-term field and recent remote sensing data sets that we combine in order to assess the following questions: What are the spatial patterns of ice loss and gain? What

are the variability and trends of ice loss and gain through time? What glaciers are representative of and can serve as indexes of the changes taking place among the larger population of glaciers? Do all Denali glaciers exhibit a melting trend attributable to global or regional climate change?

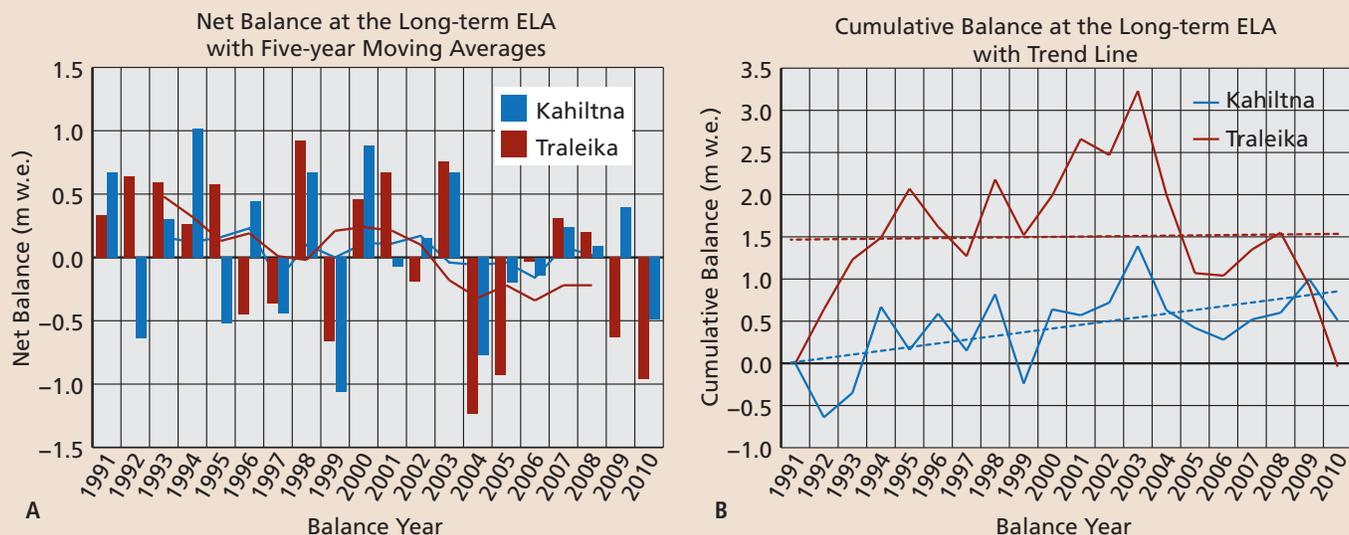
## Mass balance measurements

Direct field measurements are a vital component of long-term glacier monitoring programs. At the end of the winter accumulation season, glaciologists probe snow depths, dig pits, and measure snow density to determine the mass gained on the glacier over winter (winter balance). To track ablation these scientists install vertically oriented stakes in the snow and ice surface and revisit these locations to determine the change of the surface relative to the height of the stake (fig. 1). These changes are converted to water-equivalent

values based on knowledge of the density of snow or ice that has accumulated or ablated at that place. Snow and ice ablated during the summer is termed summer balance. The units for water equivalent values are meters water equivalent (m w.e.). The sum of the winter and summer balances is the net balance, which is a measure of the annual gain or loss. Researchers then extrapolate the point observations to the entire glacier surface, based on measured or assumed gradients in the various mass balance terms, and calculate the mass balance of the entire glacier. Data from that glacier may be used to represent other unmeasured glaciers in a region. Glaciers chosen to represent broader regions in this way are known as “index glaciers,” and are usually chosen based on their location, physical characteristics, and ease of access.

In Denali National Park, Larry Mayo (formerly of the U.S. Geological Survey), and Keith Echelmeyer (formerly of the University of Alaska–Fairbanks) chose the Kahiltna and Traleika glaciers as appropriate indexes because they capture a broad range of elevation and climate gradients spanning from the south to north side of the Alaska Range (Mayo 2001). These researchers established a single observation site on each glacier near the long-term equilibrium line altitude (ELA), the approximate line at which the average glacier mass balance is zero, and they determined mass balance gradients that are used to calculate the entire glacier mass balance from this location.

Index data collected since 1991 tell the story of variability and change in space and time (fig. 2, next page). The average 1991–2010 net balance at the Kahiltna Glacier site (shown in fig. 1) was  $0.19 \pm 0.27$  m w.e., showing that it is just above the long-term ELA, while the average 1991–2010 net balance at the Traleika site was  $-0.62 \pm 0.32$ , showing that it is below the long-term ELA (fig. 2A). The net balance



**Figure 2.** Net and cumulative mass balances on the Kahiltna and Traleika glaciers derived from index stake measurements show relative trends of two of Denali's largest glaciers. Graph A (left) shows the yearly net balance data adjusted to the long-term equilibrium line altitude, along with the five-year moving averages (solid lines). Graph B (right) shows the cumulative net balance and more correctly shows changes in balance that will drive advance or retreat. The trend lines show neutral to positive net balance, which is strongly tempered by the negative trend since 2004.

values are shown with their error estimates to show the relative uncertainty we have in estimating these values. We adjusted these values to the long-term ELAs using a predetermined balance gradient, yielding an approximation of the glacier-wide net balance (fig. 2A). A cumulative sum of the net balance through time shows that both glaciers generally gained mass from 1991 to 2003, but began to lose mass after 2004 (fig. 2B).

Data from each index site demonstrate the distinct precipitation gradient from the south to the north side of the Alaska Range, with significantly less winter snowfall on the north side. Traleika winter balances (average of  $0.67 \pm 0.19$  m w.e.) are 40% lower than those of Kahiltna (average  $1.08 \pm 0.12$  m w.e.).

Measurements from the Gravity Recovery and Climate Experiment (GRACE) offer estimates of regional ice loss across Alaska that can be compared with our field

observations. Implemented jointly by the National Aeronautics and Space Administration and the German Aerospace Center, GRACE examines time variations in Earth's gravitation field based on precise measurements of orbital variations of a tandem pair of satellites. Data suggest that glaciers in the portion of the Alaska Range that Denali National Park and Preserve occupies contributed about 5% to the total of ice lost from Gulf of Alaska glaciers from 2003 to 2009 (updated estimates from Luthke et al. 2008). A correlation analysis with the regional GRACE data from 2003 to 2009 shows that the Traleika balances correlate better with the GRACE data, indicating Traleika is more representative of regional conditions than Kahiltna. Further index monitoring and GRACE data, along with current and future research, will help elucidate the relationship of these data to temporal and spatial patterns of other glaciers and climate in the Alaska Range.

## Repeat laser altimetry profiling

Using airborne laser and lidar, we have measured elevation profiles along the centerline of a large number of glaciers in the Alaska Range at multiple times between 1995 and 2010. These profiles reveal the range and distribution of glacier change and highlight different glacier responses occurring in various geographic settings. In Denali National Park and Preserve the data set includes repeated profiles on a total of 13 glaciers, with the most extensive data on Muldrow and Kahiltna glaciers. In the most recent measurement interval, 2007–2010, Kahiltna laser profiles indicate little change in surface elevation and hence volume, which is in close agreement with the relatively steady mass balance measured at the index site for that period (fig. 2B). Some minor elevation increases (~10 m) were detected on a small portion of lower reaches of the Kahiltna, likely related to localized ice flow dynamics. On



studies (Hartmann and Wendler 2005; Arendt et al. 2009). However, the extent to which climate changes are expressed as fluctuations in glacier area is complicated by the unique dynamics, geometry, and surface cover of each glacier. For example, many glaciers have a significant amount of debris covering their lower reaches and terminus areas, which can significantly alter terminus response. In addition nearly all the large glaciers on the north side of the mountain system are surge type, periodically transporting large amounts of accumulated mass from an upper reservoir area to the lower terminus area. In the 55-year period documented here, the Muldrow, Peters, and two unnamed glaciers to the east of Muldrow Glacier experienced surge events that caused significant terminus advance (shown in blue in fig. 3). Other glaciers have surged over this time but not with enough volume to cause a significant increase in area.

## Repeat photography

Repeat or comparative photography (fig. 4) is a powerful method for documenting and communicating glacier change, allowing us to relate the trends we are seeing with index, altimetry, and extent data. We see substantial change in the small and medium-sized glaciers at lower elevations. A dramatic example is the East Teklanika Glacier, a small valley glacier that has retreated a great deal in the last century. Other striking examples include Polychrome, West Fork Cantwell, Sunset, and Hidden Creek glaciers. In the case of Muldrow Glacier, an aerial photo pair shows the terminus only a couple of years after the surge and then after 47 years of melting and downwasting (see fig. 4). From farther up on Muldrow Glacier, a photo pair shows notable loss of glaciers mantling the mountainside above it, but not thinning of the trunk glacier itself.

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*Glacier dynamics will always be strongly influenced by local features such as terrain, elevation, and local weather patterns, but larger-scale climatic patterns and trends will dominate long-term glacier change.*

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## Comparison to climate trends

Climate in much of Alaska is strongly driven by seasonal to decadal variations in sea surface temperature of the Pacific Ocean. A multidecadal oscillation driven by these variations is known as the Pacific Decadal Oscillation (PDO), which is an index that tracks anomalies in Pacific Ocean sea surface temperatures (Mantua et al. 1997). The PDO oscillates between positive and negative phases on a 20- to 30-year cycle. In Alaska the positive phase of the PDO generally corresponds with higher air temperatures (particularly winter temperatures) and increased cloudiness and precipitation, whereas the negative phase tends toward cooler and drier climate averages (Hartmann and Wendler 2005).

A look at regional climate data illustrates the effect of PDO phase shifts on long-term trends. Between 1951 and 2001 there was a 1.7°C (3.1°F) increase in the mean annual air temperature in interior Alaska, with the greatest increases occurring in winter and spring (Hartmann and Wendler 2005). The increasing trend is largely explained by the shift from a negative phase of the PDO (1945 to 1976) to a positive phase (1976 to 2005). Thus climate trends related to PDO phase shifts (and other large-scale climate oscillations) must be considered carefully when calculating climate averages, establishing climate-glacier relationships, and interpreting global climate change and warming trends

in Alaska. We note that the data on which these trends are based are from relatively low-lying areas and are not necessarily representative of the mountains that the glaciers occupy.

The glacier and climate link may show us trends in mountainous regions of Alaska. Arendt et al. (2009) found that 76% of 46 glaciers measured with repeat laser altimetry across Alaska showed increased rates of ice loss since the mid-1990s, with loss driven by increased summer temperatures. Likewise, the benchmark glaciers (Gulkana and Wolverine) monitored by the USGS show increased rates of ice loss since the late 1980s (Van Beusekom et al. 2010). Before 1989, mass balance values of Wolverine Glacier (and South Cascade Glacier in Washington State) correlated well with the PDO index; however, a dramatic increase in the rate of loss (driven by increases in summer temperatures) since 1989 appears to be less tied to the PDO and other large-scale climate oscillations and is likely forced by global-scale climatic changes (Rasmussen and Conway 2004).

The mass balance data on Kahiltna and Traleika glaciers do not show dramatic losses since 1991 as many other glaciers in Alaska do. We note that unlike the Wolverine and Gulkana glaciers, these glaciers have very high-altitude accumulation areas (on the upper reaches of Mount McKinley) and thus are very cold and less prone to changes from rising temperature trends. Comparing the periods before and

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NPS/IRON D. KARPLO

**Figure 4.** Modern photos of glaciers compared with images taken from early scientists and explorers help researchers interpret long-term rates of change. From top to bottom, left to right in pairs: Muldrow Glacier terminus 1959 (soon after the 1956–1957 surge) and again in 2006, Teklanika Glacier 1919 and again in 2004.

after the 1976 PDO-induced climate shift, there was an approximately 20% increase in autumn and winter precipitation that would have offset some of the effects of the increased air temperatures. We also note that average annual temperature for Alaska's interior region from 1976 to 2001, although shifted above the 1951 to 1976 values, reveals a slight decreasing trend (Hartmann and Wendler 2005). This, together with the snowfall increases, could explain the mass balance observations on Kahiltna and Traleika, which indicate cumulative mass gains during a portion of that period (fig. 2B).

The loss of glacier mass in the smaller, lower-altitude glaciers in the eastern portion of the park (as seen in the repeat photography) is in part due to the shift

from the cold period known as the Little Ice Age (16th to 19th centuries) to the warmer 20th century. Continued loss of glacial mass from about 1952 to present may be driven by the temperature increase associated with the 1976 shift in PDO. Analysis of terminus retreat on two of Denali's eastside glaciers shows West Fork Cantwell Glacier has been retreating at a constant rate from about 1950 to present and Middle Fork Toklat Glacier has been retreating at an increased rate from 1992 to 2002. Unfortunately, more recent volume loss data for these smaller glaciers and others in the vicinity are not available to indicate if the rate of ice mass loss has increased since the mid-1990s as on many other glaciers in Alaska. Further research and monitoring may elucidate these rates.

## Summary and conclusion

Monitoring glacier behavior and trends using a variety of techniques provides insight into the complexity of glacier change and increases our ability to distinguish local effects from regional and global trends. Formal glacier monitoring in Denali began in 1991 and has tracked mass balance trends on two large valley glaciers, with trends neutral to positive from 1991 to 2003 and negative since 2003. Parkwide analysis of glacier extent change since the 1950s indicates a consistent trend of glacial retreat, except for glaciers that have surged. Longitudinal surface elevation profiling and repeat photography reveal relative stability in larger glaciers, but dramatic long-term mass loss on small, relatively low-elevation, valley glaciers characteristic

of the eastern portion of Denali National Park and Preserve. These patterns of ice loss are somewhat unique to the western interior Alaska Range and on the larger glaciers appear to contrast with increasing rates of ice loss from USGS benchmark glaciers and large glaciers that border the Gulf of Alaska.

Continued glacier monitoring, along with enhanced climate monitoring, will allow for correlations between climate and glaciers to be refined. Glacier dynamics will always be strongly influenced by local features such as terrain, elevation, and local weather patterns, but larger-scale climatic patterns and trends will dominate long-term glacier change. Projected climate change scenarios up to the year 2080 for Denali indicate a possible increase in summer temperature of 3°C (5.4°F) and a 25% increase in winter precipitation, along with a 6°C (10.8°F) increase in average winter temperature (SNAP 2009). This scenario uses the “intermediate” CO<sub>2</sub> emissions scenario (A1B) from the IPCC Special Report on Emissions Scenarios (Nakicenovic and Swart 2000). Glacier mass balance modeling will be required to determine whether the projected temperature increases would be offset by the increased amount of precipitation. In addition the National Park Service is evaluating the likely impacts on visitation and recreation, along with changes to hydrologic and geomorphic conditions and dependent habitats.

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# Climate change, management decisions, and the visitor experience: The role of social science research

By Matthew T. J. Brownlee and Kirsten M. Leong

**P**ARK PROFESSIONALS ARE CONFRONTED with complex climate change scenarios that require decisions based on the best available science. Professional staffs often use field-based data to inform management decisions, and social scientists have long gathered this information. For example, the NPS Social Science Branch of the Environmental Quality Division oversees the Visitor Services Project that regularly collects basic information about visitors (e.g., visitation characteristics and history, visitor preferences, visitor demographics, and spending patterns) at many park units. As a result, park professionals have used social science information to contribute to decisions, such as facility and service improvements, site-specific visitor regulations, and information dissemination. In the context of climate change, park professionals may need more specific information about visitors' knowledge, beliefs, attitudes, motivations, and behavior to inform approaches to visitor management, messaging, education, and outreach. In this article, we outline current and potential social science research contributions to assist park staffs in effective decision making about climate change.

## Toward effective decision making

The NPS Climate Change Response Program (CCRP) reveals that as conditions shift, "effective decision making will require a flexible approach for incorporating new and relevant science" (CCRP 2010). In 2009 the National Research Council (NRC) identified six principles for effective decision making that are neces-

**Abstract**  
Park professionals often use field-based data to inform management decisions, and social scientists have long gathered this information. As park staffs confront the new challenge of climate change, information developed through social science research will enable them to make more effective management decisions. Using six principles identified by the National Research Council and incorporated by the NPS Climate Change Response Program, we outline current and potential social science research contributions to assist park staffs in effective decision making about climate change. As society's understanding of and responses to climate change evolve, social science will be a crucial tool to assist both young NPS employees and veteran park professionals in effectively making decisions and communicating them in response to climate change in parks.

**Key words**  
climate change, park management, social sciences, visitor experiences

sary for a flexible approach, and recently the National Park Service outlined these principles in its strategy to address climate change (CCRP 2010). In the following sections, we explain how social science applications can facilitate inclusion of these principles for park staff responding to climate change (e.g., reducing a park's carbon footprint, increasing awareness of visitors and staff, climate change scenario planning). Additionally, table 1 (next page) matches principles of effective decision making with social science methods that can provide needed information and insight.

## *Begin with managers' needs*

The first principle recommends *beginning with managers' needs* so the necessary tools (e.g., on-site visitor surveys; see table 1 for examples of additional tools) can be prescriptively developed to provide desired outcomes (e.g., information about visitors' perceptions of site-specific

climate-sensitive resources). Addressing specific management needs is a hallmark of the social science research process. For example, social scientists often first conduct qualitative interviews or focus groups with park staff to inform the development of a quantitative visitor survey (i.e., Instrument Development Approach; Creswell and Plano Clark 2011). This approach has proved effective in helping park professionals manage and understand the visitor experience within a climate change context. For example, researchers (Brownlee and Hallo 2011) used in-depth interviews with professionals at Kenai Fjords National Park (Alaska) to identify their information needs regarding visitors' opinions about climate change. During this process, park staffs were able to express clearly what they wanted to know about visitors' opinions of climate change. Research questions included: What are visitors' levels of perceived awareness about global climate change issues, beliefs about anthropogenic causation, and awareness of climate impacts to sensitive resources at Kenai Fjords?

**Table 1. Typical social science methods that can address principles for effective decision making**

Examples of Social Science Methods	Principles for Effective Decision Making					
	Begin with Managers' Needs	Give Priority to the Process	Link Information Providers and Users	Build Connections Across Disciplines and Organizations	Enhance Institutional Capacity	Design for Learning
Park-specific surveys (telephone, mail, Internet, face-to-face)	X		X			X
Topic-specific interviews and oral histories	X	X	X	X		X
Focus groups and workshops that engage multiple perspectives	X	X	X	X	X	X
Content analysis of existing information, blogs, and public comments	X		X	X	X	X
Evaluating effectiveness of existing education (e.g., citizen science programs) and interpretive programming	X	X			X	X

*Note:* This table is not intended to be inclusive of all principles for effective decision making or social science methods. Instead, the table presents the most direct relationships among decision making principles and social science methods.

Based on these interview results, researchers created a park-specific visitor questionnaire to answer these questions. Questionnaire results indicate visitors generally believe global climate change is occurring and are interested in the topic, but are unaware of the sensitivity of park resources to climate change or the biophysical changes that have occurred recently at the park (such as increased vegetation). Interpretive specialists can now focus limited resources on increasing visitors' awareness in this area. Furthermore, because the results indicate some visitors are uncertain of human influence on climate, interpretive themes may be better designed to include and target this topic as an opportunity to educate and inspire stewardship.

### *Give priority to the process as well as the products*

Second, the NRC recommends giving *priority to the process as well as products*. Specifically, the CCRP (2010) states, "By starting with the engagement process that

brings together relevant stakeholders (e.g., managers, planners, park specialists, scientists, and the public), we can encourage the development of scientific and other products that are relevant to decision making and supportive of a shared vision." Social scientists who investigate public participation emphasize the importance of matching the appropriate process with desired outcome (Chess and Purcell 1999; Leong et al. 2007). Depending on the management context, a suite of approaches can be used to engage not only visitors, but also near-park communities and relevant stakeholders, including individuals potentially most influenced by climate change in or near the park (fig. 1).

In addition to the standard public participation processes (e.g., public comment periods, community meetings) stakeholders may engage directly in climate science in parks. For example, since 2008, park professionals and researchers at Glacier National Park (Montana) have engaged park visitors and community members in climate change issues through participation in the High Country Citizen Science

Program. Specifically, participants (including high school students) help collect observational data about climate-sensitive species such as mountain goats and pikas at Glacier. Park professionals give priority to this process because "engaging the public and youth in data collection instills a strong sense of responsibility and a desire to promote resource conservation on behalf of the park" (Carolin et al. 2011). Social science can add significantly to this process by evaluating program effectiveness, such as increases in participants' awareness, climate change literacy, or changes in their attitudes toward climate change mitigation.

### *Link information providers and users*

The third principle is to *link information providers and users*, and social scientists working on climate change issues (i.e., information providers) can provide critical information for park professionals (i.e., users). This fits well with a fundamental principle of effective park management:

MATTHEW T. J. BROWNLEE (2)



**Figure 1 (above and right).** Depending on management context, a suite of social science methodologies can be used to engage not only visitors but also near-park communities and relevant stakeholders. These include individuals potentially most influenced by climate change in or near the park.



*As society's understanding of and responses to climate change evolve, social science will be a crucial tool to assist both young NPS employees and veteran park managers in effectively making decisions and communicating them in response to climate change in parks.*

understanding visitors' opinions and perspectives. The uncertainty associated with future climate change scenarios in parks amplifies the importance of this park management principle. Specifically, park professionals may confront unforeseen scenarios caused by climate change (such as flooding or species attrition), and incorporating visitors' opinions about climate change and preferences for related management decisions may assist in effective and efficient decision making. Furthermore, park staffs charged with communicating or interpreting climate change may be more effective when equipped with a comprehensive understanding of visitors' beliefs about climate change, the causes of climate change, or the perceived role of science in their lives. While general polling results about climate change do exist (e.g., the Six Americas study), visitors to a national park are not necessarily representative of the U.S. public. Additionally, a wealth of information from the last 40 years indicates that park professionals and visitors often differ (sometimes substantially) in their opinions about resource conditions and levels of

human-related impacts (Manning 2011). Therefore, park professionals may need specific information about visitors' climate change opinions.

Currently, social science researchers (Thompson 2011) are engaged in a project to provide such information to park professionals. Specifically, researchers are conducting interviews, focus groups, and surveys with park professionals and visitors to "identify potential educational opportunities and knowledge gaps about climate change among target audiences" (CCEP 2011). This study is being conducted in six different areas of the National Park System, including some in Alaska and Florida, which both contain climate-sensitive and human-influenced resources. Park professionals will use results from this study to design specific climate change messaging for general communication planning, outreach and education, and interpretive design and delivery.

### *Build connections across disciplines and organizations*

Social scientists involved in park research often work with multiple agencies and on multidisciplinary teams, which addresses the fourth principle: *building connections across disciplines and organizations*. Often, lands managed by other agencies (e.g., USDA Forest Service) border units of the National Park System, and social scientists can assist in identifying and bridging gaps in regard to climate change that exist across cooperating agencies. For example, cooperating agencies may differ in policy responses and planning frameworks for climate change, and social scientists can use processes such as content analysis and interviews to identify these differences.

Recently, Delach and Matson (2010) compared climate change strategies and plans across the U.S. Fish and Wildlife Service, the National Park Service, and the USDA Forest Service. Specifically, researchers used a content analysis approach of each agency's climate change strategy to



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**Figure 2.** Social science evaluations can provide important and timely information that can help interpretation specialists understand the most effective climate change media and messages for their visiting audiences.

identify differences and similarities in the areas of policy, law, planning, modeling, research, partnerships, and monitoring. Researchers concluded, “Looking at the plans in tandem provides a clearer vision of the types of goals and actions needed to prepare agencies to respond to climate change than any of the three plans offer[s] alone” (Delach and Matson 2010). Such social science outcomes can help park staffs understand differences and similarities among agencies, which can inform collaborative planning processes and improve interagency connections.

### *Enhance institutional capacity*

Building connections across disciplines and agencies can additionally address the fifth principle, *enhancing institutional capacity*, which calls for adding flexibility, network building, and establishing new practices. One area that enhances institutional capacity is effective staff training (Edington et al. 2001). Recently, the NPS Intermountain Region (IMR) and social science researchers (Garfin et al. 2011) collaborated to assess climate change training needs for more than 5,000 IMR employees. Specifically, social science researchers used a structured online survey followed by semistructured interviews with IMR

employees to identify employee preferences for dissemination of training information (e.g., webinars, online resources), as well as training-related challenges to addressing climate change (e.g., cost). Furthermore, the results assisted in assessing existing Internet climate change training resources that could be used for a variety of position categories (e.g., operations, interpretation). As a result, social science researchers were able to identify the potentially most effective training methods and content to address IMR employee needs.

## Design for learning

Finally, the Climate Change Response Program and the National Research Council recommend that park staff *design for learning*, which encourages exploring alternative explanations and approaches. As park staffs learn more about visitors' opinions through social science, they may identify the most effective ways to communicate and interpret climate change to visitors (fig. 2). After park professionals design a climate change interpretation program, researchers using social science approaches such as pre- and post-participation assessments can evaluate the effectiveness of different climate change interpretation techniques. As a result, social science evaluations can provide important and timely information that can help interpretation specialists understand the most effective climate change media and messages for their visiting audience. In turn, park professionals can use relevant social science research to understand the full impact of park experiences on visitors' opinions, attitudes, and perceptions regarding climate change. Such "design for learning" processes may allow park professionals to understand alternative strategies and the efficacy of new approaches.

## Conclusion

Social scientists have increasingly contributed to effective park management over the last few decades. As park professionals confront the new challenge of climate change, data gathered through social science research will enable them to make more effective decisions. As NPS Director Jarvis indicated, "The young employees I have met who are just starting in this wonderful organization will be dealing with climate change their entire career" (CCRP 2010). As society's understanding of and responses to climate change evolve, social

science will be a crucial tool to assist both young NPS employees and veteran park managers in effectively making decisions and communicating them in response to climate change in parks.

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## RESILIENCE

# Conserving pinnipeds in Pacific Ocean parks in response to climate change



By Sarah Allen, Eric Brown, Kate Faulkner, Scott Gende, and Jamie Womble

**Figure 1.** Harbor seals rest on an iceberg calved from a glacier (inset) in Glacier Bay National Park, Alaska.

**C**LIMATE CHANGE WILL LIKELY have a profound impact on resources in Pacific Ocean national parks. Changes are predicted to occur in sea-level rise, food webs, community structure of marine organisms, and oceanographic processes. Nevertheless, predicting the nature or extent of these changes and their impacts is highly uncertain (Stephenson et al. 2010). For example, sea temperature, salinity, and ocean circulation are expected to change, but because they are inter-related and vary spatially and seasonally, scientists expect “unexpected” responses by organisms (NRC 2002). Most scientists, though, agree that ocean and coastal conditions, including those in Pacific Ocean parks, will be altered over the coming decades as a result of climate change (Larger et al. 2011; Learmonth et al. 2006; see <http://www.nature.nps.gov/climatechange/effects.cfm>). Ocean parks of the National Park System have common oceanographic and biological settings and related vulnerabilities to changes in climate, and staffs

are seeking ways to coordinate response strategies. Here we consider the potential impacts of climate change on pinnipeds (seals and sea lions) that occur in some 18

national parks around the Pacific Ocean from Hawaii to Alaska, and the role that the National Park Service can play in conserving this group of marine mammals.

## Abstract

The evolutionary record from previous climate perturbations indicates that marine mammals are highly vulnerable but also remarkably adaptable to climatic change in coastal ecosystems. Consequently, national parks in the Pacific, from Alaska to Hawaii, are faced with potentially dramatic changes in their marine mammal fauna, especially pinnipeds (seals and sea lions). Impacts of climate change on pinnipeds may be manifest in changes in sea temperature, sea level, incidence of storm surge, ocean acidification, loss of glacial ice, and alterations in oceanic processes such as the frequency of El Niño events. These potential changes portend challenges to park management in responding to loss of habitat, mass strandings of sick or dead pinnipeds, alterations in prey availability, or range shifts with species expanding into or contracting out of national parks. The National Park Service could benefit from a regional approach to guide parks with a suite of actions to help conserve pinniped populations in response to climate change: (1) increased information and modeling to forecast pinniped habitat at risk, (2) increased protection via designation of marine protected areas, (3) restoration of degraded habitat, and (4) communication with the public. Since parks are islands in a larger seascape, coordination with other agencies and groups that also manage for pinniped conservation is essential.

## Key words

adaptive management, climate change, El Niño, habitat loss, marine protected areas, pinniped, sea-level rise, sea lions, seals

**Table 1. Pinnipeds that occur in national parks of the Pacific Ocean\***

Common Name	Scientific Name	Parks	Breeding
Monk seal	<i>Monachus schauinslandi</i>	Hawaii Volcanoes NP** Kalaupapa NHP Kaloko-Honokōhau NHP Pu'uhonua o Hōnaunau NHP	X
Northern elephant seal	<i>Mirounga angustirostris</i>	Point Reyes NS Golden Gate NRA Channel Islands NP	X X
Harbor seal	<i>Phoca vitulina</i>	Aniakchak NPres Glacier Bay NP Katmai NP Kenai Fjords NP Klondike Goldrush NHP Lake Clark NP Wrangell–St. Elias NP Olympic NP Lewis and Clark NHP Redwood NP Point Reyes NS Golden Gate NRA Channel Islands NP Cabrillo NM	X X X X X X X X X X X X X
Steller sea lion	<i>Eumetopias jubatus</i>	Aniakchak NPres Glacier Bay NP Katmai NP Kenai Fjords NP Klondike Goldrush NHP Lake Clark NP Wrangell–St. Elias NP Olympic NP Redwood NP Point Reyes NS*** Channel Islands NP***	X X X X X
California sea lion	<i>Zalophus californianus</i>	Glacier Bay NP Olympic NP Lewis and Clark NHP Redwood NP Point Reyes NS Golden Gate NRA Santa Monica Mountains NRA Channel Islands NP	X
Northern fur seal	<i>Callorhinus ursinus</i>	Channel Islands NP	X
Guadalupe fur seal	<i>Arctocephalus townsendi</i>	Channel Islands NP	X

\*Parks in the Pacific Ocean where pinnipeds do not occur or sightings are accidental include National Park of American Samoa, War in the Pacific NHP, USS *Arizona* Memorial, Haleakalā NP, and Pu'ukoholā Heiau NHS.

\*\*NHP = national historical park, NM = national monument, NP = national park, NPres = national preserve, NRA = national recreation area, NS = national seashore.

\*\*\*Sea lions occurred here and gave birth within the past 40 years.

Pinnipeds occur throughout the Pacific Ocean and range from critically endangered monk seals (*Monachus schauinslandi*) that use select sites in several Hawaiian Island parks to the more cosmopolitan harbor seals (*Phoca vitulina*) that use a diversity of habitats in parks from Alaska to California (table 1; figs. 1 and 2). This group of marine mammals faces unusual challenges because they rest and pup (“haul out”) on land and ice but forage at sea, sometimes in close proximity to haul-outs, but often traveling great distances to feed. Although the National Park Service manages only a fraction of the total area needed for effective conservation of these species, it manages some key habitats for pinnipeds, which affords them extra protection for reproduction and survival. To this end, a specific

management strategy for pinnipeds within parks in collaboration with other management agencies is needed. We first describe linkages between climate change and pinniped abundance and distribution in national parks, and then highlight four specific roles that parks can play that will aid in conserving these animals and their habitats.

## Climate change effects on pinnipeds

Pinnipeds are unique marine mammals because they spend much of their life at sea but require land or ice to give birth. Consequently, climate change may affect their distribution and abundance through direct pathways, such as loss or gain of terrestrial

and ice habitat needed for resting and birthing, or indirect pathways, such as changes in prey availability or incidence of disease via altered ocean conditions (Learmonth et al. 2006). Projected changes on pinniped distribution may have both positive and negative effects, a glimmer of which is now noticeable (Simmonds and Isaac 2007).

Recent research demonstrates how climate change is already influencing habitat availability for pinnipeds in Pacific Ocean parks. The Muir Glacier, for example, an actively calving glacier in Glacier Bay National Park, Alaska, has receded from saltwater and “grounded” in the past few decades (Hall et al. 1995). Prior to this grounding, investigators counted more than 1,300 seals in upper Muir Inlet (Streveler 1979), but because of loss of icebergs, that number is now zero (Mathews 1995; Womble et al. 2010). Although the relationship between calving glaciers and climate is complex (Post et al. 2011), ice sheets that feed glaciers in Glacier Bay have undergone rapid loss of ice and retreat over the last 200 years (Hall et al. 1995; Larsen et al. 2007). If loss of ice-associated habitat continues as predicted (Larsen et al. 2007), seals in Glacier Bay, which still use ice calved from the Johns Hopkins Glacier, will be forced to use terrestrial substrate for breeding or move out of the park to find glacial ice in other areas. Factors such as increased exposure to land-based predators and reduced breeding success, as has been demonstrated for other pinnipeds (e.g., Jüssi et al. 2008), may result if available ice is reduced. Changes in



**Figure 2.** A pinniped colony enjoys a remote beach at Channel Islands National Park.

NPS/SARAH ALLEN

NPS/JOHN LONGSTRETH

NPS/HEATHER JENSEN



**Figure 3.** A large landslide in 2006–2007 (left) at an elephant seal colony at Point Reyes created habitat (right) for seals breeding in 2008 and 2009.

**Figure 4.** An elephant seal colony is inundated at Point Reyes during the 1998 El Niño, drowning pups.

seal numbers and distribution within the park may not necessarily affect the overall regional population of seals. For the least adaptable pinnipeds such as ice-dependent species, scientists expect negative effects from changes in climate; on the other hand, climate change could affect pinnipeds positively if it opens suitable habitat for species with expanding ranges (Harington 2008; Simmonds and Isaac 2007). Similarly, inundation of low-lying areas might provide access to previously inaccessible inshore areas or nearshore islands.

Changes in ocean conditions also have affected the suitability of some substrates for pinnipeds in Channel Islands National Park and Point Reyes National Seashore. Sea-level rise of 20 cm (8 in) over the past century in California (Largier et al. 2011), coupled with storm surge, has altered some habitats by inundating low-lying areas and eroding shorelines used by pinnipeds (figs. 3 and 4). Similar exposure to sea-level rise is expected for monk seals in the Hawaiian Islands (Baker et al. 2006).

El Niño events in the Pacific offer a glimpse at the complex effects of globally warmer sea temperatures on pinnipeds and presage likely scenarios for these animals. During past El Niño events in 1982 and 1998, pinniped productivity and survival declined significantly at Channel Islands and Point Reyes because of reduced prey availability or storm-driven tidal inundation, which drowned pups (Trillmich and Ono 1991; Sydeman and Allen 1999) (see fig. 4). With ocean warming, El Niño events are project-

ed to increase in frequency and intensity (Trenberth and Hurrell 1994; Bakun 1990). Additionally, harmful algal blooms during the 1998 El Niño event resulted in spikes in the number of sick and dead sea lions that became stranded on park beaches in California (Gulland et al. 2002). Such harmful algal blooms, likely linked to climate change and warmer sea temperatures, have increased over the past three decades (Van Dolah 2000).

## Conservation strategies

The evolutionary record from previous climate perturbations indicates that marine mammals are both highly vulnerable and remarkably adaptable to changes in coastal ecosystems (e.g., Harington 2008). Generalist and cosmopolitan species such as harbor seals are greatly adaptable and may simply move elsewhere or use newly formed habitat when other areas become degraded. In contrast, obligate species such as ice breeders, or those with reduced numbers, including endangered species, may be less resilient to changes in the environment. Whether managing for pinniped generalists or obligates, park staffs will be challenged to preserve and protect species and their habitats in a rapidly changing climate.

In concert with conservation strategies of other agencies and organizations, we propose four key strategies for the National Park Service that will assist in assessing the magnitude of climate change impacts on pinnipeds and contribute to their conserva-

tion both in parks and across their range: (1) adaptively monitor pinniped populations and linkages to environmental conditions; (2) reduce anthropogenic stressors such as physical disturbance and fisheries interactions; (3) restore pinniped habitats; and (4) communicate with and engage the public about these strategies.

First, the National Park Service needs to expand its efforts to collect data on population dynamics, pup production, disease status, and habitat condition of pinnipeds in the National Park System (Burek et al. 2008). This would contribute to better estimates of species abundance and also better forecasting of impacts from climate scenario modeling. A long history of monitoring pinniped population trends by other agencies and by the National Park Service in several national parks (Brown et al. 2011; Womble et al. 2010; Sydeman and Allen 1999) already provides critical baseline information for interpreting the influence of climate change on these species. Most coastal parks, though, lack pinniped studies that link population data with current and future environmental conditions. Glacier Bay National Park recently partnered with the National Marine Mammal Laboratory to develop and implement an aerial photography monitoring program that records not just the abundance and spatial distribution of seals but also ice conditions and substrate availability for pupping. Similar studies that link pinnipeds with environmental conditions, including changes in oceanography and shoreline, could be augmented or initiated at other parks.

NPS/ERIC BROWN



**Figure 5.** Two monk seal mothers and their pups haul out along a narrow stretch of beach at Kalaupapa National Historical Park.

Second, establishment of marine protected areas (MPAs) and special area closures for pinnipeds are management options that can reduce tangential threats, such as direct interactions with humans and disturbance from coastal development and fisheries, and have been successfully implemented in a few ocean parks. For example, in Johns Hopkins Inlet in Glacier Bay National Park, the National Park Service restricted all vessel traffic during the pupping season to protect harbor seals during this critical period. At Point Reyes, kayaks were similarly prohibited in Drakes Estero during the harbor seal pupping season. The Park Service can also work to evaluate the benefits to pinnipeds of reducing or eliminating commercial fishing in or adjacent to national parks. Commercial fishing can result in localized depletion of pinniped prey, even if the fisheries are sustainable at a larger scale (NRC 2006; Womble et al. 2009).

Unfortunately, indirect benefits of marine protected areas to pinnipeds, such as prey availability, are difficult to measure and relationships are complicated. For example, monk seals appear to suffer from competition with large predatory fish in a marine reserve in the northwestern Hawaiian Islands whereas they benefit from commercial extraction of large fish in the main Hawaiian Islands (Parrish et al. 2008). This seal species has also benefited from restricted access to specific breeding sites such as Kalaupapa National Historical Park (Brown et al. 2011). Similarly, at Golden Gate National Recreation Area, California, the rate of disturbance has decreased as

seal numbers have increased where human traffic was restricted in 2007 at a harbor seal colony (Flynn et al. 2009). Clearly, research on the effects of marine protected areas in specifically conserving pinnipeds needs close scrutiny and further study on a case-by-case basis.

The creation of a global network of marine protected areas may be more broadly effective in the protection of mobile marine mammals (Hoyt 2011), and one study showed that setting aside a small fraction of the oceans could result in conservation of more than 80% of the world's marine mammals (Pompa et al. 2011). The National Park Service has been engaged in establishing networks of marine protected areas with other agencies so that national parks can serve as refuges in the larger seascape. One such example is the International Committee for Marine Mammal Protected Areas, an international body working toward creating, maintaining, and understanding the effectiveness of protected areas for marine mammals. The State of California, in collaboration with Channel Islands National Park and Point Reyes National Seashore, has established networks of MPAs coincident with pinniped colonies. A network of protected areas that involves national parks around the Pacific Rim could enhance the resilience and perpetuation of ecologically intact coastal ecosystems. Although national parks manage only a fraction of the total range of any given pinniped species, these spatially dispersed refuges enhance a fundamental MPA goal: to preserve ecological integrity. Similarly they are consistent with pinniped conservation given that these marine mammals, as apex predators, are often indicators of healthy marine ecosystems (NOAA 2008).

Third, the National Park Service can actively restore degraded habitats. Restoration of coastal habitats and removal of nonnative species enhance suitable places for pinnipeds to congregate onshore, and

surprisingly, there are a number of areas in national parks that would benefit from active restoration. At Kalaupapa National Historical Park, for example, the removal of cattle, coupled with fencing of beaches to restrict feral ungulates, has coincided with the emergence of a productive pupping area for monk seals (Brown et al. 2011; fig. 5). Large-scale restoration projects such as the Elwha Dam removal at Olympic National Park, Washington, will extend benefits to regional coastal ecosystems and species, including seals and sea lions. Pinnipeds attracted to restored park habitats would further benefit from the added protection afforded by the National Park System.

Finally, key to any adaptive management approach is to ensure that risks, strategies, and potential outcomes are explored and developed with involvement of interested communities and other management groups and then communicated with the public. In Pacific Ocean parks, a group of interpreters (Pacific Ocean Education Team, POET) was organized in 2008 to identify issues important for ocean stewardship and to serve as a voice for park managers to advance strategies for conservation of marine mammals. Pinnipeds specifically, and marine mammals in general, are a highly sought-after viewing experience for visitors to Pacific Ocean parks, and the connection they make with marine mammals is an effective opportunity to convey facts regarding climate change impacts on national park resources. Communicating this message and coordinating actions with other organizations will ensure a consistent message for public understanding.

## Conclusion

Historically, national parks were managed in isolation with the idea that local anthropogenic influences on their resources could be tempered. However, climate change,

pollution from distant sources, large-scale changes in land use patterns, and other environmental factors have altered this perception, and recent publications have highlighted the need not just to accept that change is forthcoming but also to develop proactive coping strategies (Aplet and Cole 2010). We hope to build on these strategies for conserving pinnipeds in Pacific Ocean parks, recognizing that the National Park Service plays an important role in the conservation of these marine mammals and their coastal habitats with a changing climate.

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# The George Melendez Wright Climate Change Fellowship Program: Promoting innovative park science for resource management

By Gregg Garfin, Lisa Norby, Lisa Graumlich, and Tim Watkins

**A REPORT BY THE U.S. CLIMATE** Change Science Program (now the U.S. Global Change Research Program) concluded, with very high confidence, that “terrestrial and marine systems are already being demonstrably affected by climate change” (Janetos et al. 2008). Observable impacts, such as glacier retreat (Watson et al. 2008), changes in growing season length, phenology, and species distributions, have been documented in U.S. ecosystems (e.g., Inouye 2008), including national parks. In order to improve the quality of science-based resource management information available to National Park Service (NPS) resource managers, and to increase the understanding of park resources, the National Park Service established the George Melendez Wright Climate Change Fellowship in 2010. This program supports new and innovative research by graduate students on impacts of climate change on protected areas.

## Program overview

Applicants were required to describe their research goals, methods, products, and justify their budget requests; in addition, they were required to describe the relevance of their proposed research to national park resource conservation and to garner sponsorship from the parks in which proposed research was to be conducted. Twenty-two fellowships, totaling \$300,245, were awarded, from more than 140 proposals submitted in spring 2010 (table 1, next page). Program-sponsored research is being conducted in 31 national

parks in the following NPS regions: Pacific West (11), Intermountain (5), Alaska (3), Northeast (1), Southeast (2); one Pacific West project is in Hawaii. In addition to NPS sponsorship of the program, outside grants, fellowships, and awards garnered by the 2010–2011 fellowship winners added \$262,760 to the total resources available for their research. These additional funds added substantially to the value provided by the NPS investment in the fellowship program. The first-year program is administered by the University of Arizona, and project descriptions can be found at <http://www.nature.nps.gov/climatechange/internshipsresearch.cfm>. The 2011–2012 program, for which 11 finalists were recently selected, is administered by the University

of Washington ([http://coenv.washington.edu/students/melendez\\_wright/](http://coenv.washington.edu/students/melendez_wright/)).

## Projects overview

The research projects cover a wide variety of topics, observational methods, and experimental approaches. We categorized the fellowship projects into the following subject areas: glaciers (2), park policy (1), vegetation studies (10), and wildlife (9). The glacier studies focus on glacier mass balance and measurement of physical processes related to fluctuations in glacier mass and extent. The park policy study uses document review and interviews to analyze a process to make multijurisdic-

### Abstract

In 2010 the National Park Service Climate Change Response Program created the George Melendez Wright Climate Change Fellowship to foster new and innovative research on climate change impacts in protected areas, and to promote national parks as laboratories for research on climate change. The program aims to increase the use of scientific knowledge to further resource management in parks and deepen the utility of place-based science for society in national parks. In its first year the program funded 22 proposals by graduate students from across the country. Research in progress covers an extensive variety of topics, from examination of how genetic factors mediate climate change effects in vulnerable tree species to ethnographic studies of the effects of environmental change on the practices of subsistence fisheries in coastal preserves and monuments. The geographic and ecosystem extent of projects ranges from Hawaiian cloud forests and Alaskan alpine environments, to forests in the Intermountain West, to coastal wetlands in Louisiana. Most program fellows have made field collections and are in the process of analyzing data. Preliminary results document the sensitivity of vegetation in the cloud forests of Haleakalā National Park to drought, California seashore vulnerabilities, and a variety of climate and ecological impacts on subsistence fisheries in Alaska.

### Key words

climate change, climate impacts, fellowship program, resource management, parks for science, science for parks

**Table 1. George Melendez Wright Climate Change Fellows and projects for 2010–2011\***

Name	Institution	Title
Kate Boersma	Oregon State University	Climate-induced top predator extinctions affect aquatic community structure in arid headwater streams
Helen Bothwell	Northern Arizona University	Long-term vulnerability and risk assessment of a key habitat type throughout the western U.S.: Cottonwood riparian areas
Brian Cheng	University of California–Davis	Community responses to global change
Danielle Christianson	University of California–Berkeley	Linking climate change to forest dynamics from seedling-to-ecosystem scales
Sarah Corman	Brown University	Salt-marsh phenology and productivity in a changing climate
Shelley Crausbay	University of Wisconsin–Madison	Variation in water stress at the upper limit of cloud forest along a secondary climate gradient, Haleakalā National Park
Kristen Dybala	University of California–Davis	Impacts of climate change on avian population dynamics: A bottom-up approach
Ailene Kane Ettinger	University of Washington	Testing the limits: Effects of climate and competition on conifer distributions at Mount Rainier
Kevin Ford	University of Washington	Climate change and range shifts of subalpine and alpine meadows at Mount Rainier National Park
T. J. Fudge	University of Washington	Quantifying shrinking glaciers in Olympic National Park: Impact on summer streamflow
Sarah Olverson Hameed	University of California–Davis	Climate change implications for natural communities: A management question at Point Reyes National Seashore
Yu-Hsin Hsueh	Louisiana State University	Rainfall events in a hummocky terrain may release saltwater stress of bald cypress ( <i>Taxodium distichum</i> L. Rich) in the Barataria Wetland, Louisiana
Shawn Johnson	University of Michigan	Building knowledge at the landscape scale: Glacier National Park and its neighbors
Allison Kidder	University of California–Berkeley	Water relations of <i>Baccharis pilularis</i> D.C. seedling establishment in a changing climate
Tyler Lewis	University of Alaska–Fairbanks	Ecosystem change in boreal wetlands and its relation to wetland birds
Amy Luxbacher	University of Minnesota–Twin Cities	Modeling the past as a window to the future: A study of how climate fluctuations have influenced the distribution and demographic history of the montane salamander, <i>Plethodon jordani</i>
Kaitlin Maguire	University of California–Berkeley	Mammalian distribution and niche dynamics in relation to climate change during the Miocene, John Day Fossil Beds
Katie Moerlein	University of Alaska–Fairbanks	Local observations of climate change and impacts on subsistence fisheries in Noatak, Alaska
Adam Springer	University of Arizona	Using historical data to evaluate the effect of climate change on perennial vegetation in Saguaro National Park
Morgan Tingley	University of California–Berkeley	Long-term trends in the avifauna of the Sierra Nevada: Community dynamics in three national parks over a century of climate change
Jennifer Wilkening	University of Colorado–Boulder	Estimating climate-mediated stress in a sentinel species and NPS key vital sign
Joanna Young	University of Alaska–Fairbanks	Effects of changing climate on Denali Park glaciers: A case study on the Kahiltna Glacier

\*For brief project descriptions, see <http://www.nature.nps.gov/climatechange/internshipsresearch.cfm>.



KATIE MOERLEIN

**Figure 1.** This aerial photo of the community of Noatak, Alaska, located on the west bank of the Noatak River shows Cape Krusenstern National Monument in the background. From Katie Moerlein's GMW CCFP project, "Local observations of climate change and impacts on subsistence fisheries in Noatak, Alaska."



SHELLEY CRAUSBAY

**Figure 2.** This apparatus measures the sap flux velocity of 'Ōhi'a (*Metrosideros polymorpha*) in Haleakalā National Park's cloud forest. From Shelley Crausbay's project, "Variation in water stress at the upper limit of cloud forest along a secondary climate gradient, Haleakalā National Park."



MEISSALACEY

**Figure 3.** Western hemlock (*Tsuga heterophylla*) seedling, from Ailene Kane Ettinger's project, "Testing the limits: Effects of climate and competition on conifer distributions at Mount Rainier."

tional landscape-scale management decisions in the face of climate change. The vegetation studies examine observed and potential changes in species distribution, genetics, forest composition, productivity, physiology, and phenology in environments ranging from coastal salt marshes to alpine meadows. The wildlife studies examine a wide range of organisms, including amphibians, insects, mollusks, birds, fish, and mammals, in a correspondingly wide range of habitats. The botanical and wildlife research uses such techniques as field surveys, laboratory and field experiments, physiological assays, and modeling.

## Preliminary research results

For the 2010–2011 program, funds were disbursed during late spring and early summer. Most program fellows have made initial field collections or observations and are in the process of analyzing data or gearing up for 2011 field seasons. The following examples highlight preliminary research results, submitted in November 2010, from selected projects. (Note: These results have not yet been published or peer-reviewed.)

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### *Preliminary results demonstrate . . . improved understanding of the mechanisms underlying climatic and ecological impacts in national parks.*

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To answer questions about the effect of climate and ecological changes on the subsistence fisheries used by indigenous peoples in northwestern Alaska parks and preserves, Katie Moerlein observed Inupiaq Eskimo fishers and hunters in Noatak (fig. 1). She documented their concerns and interviewed them to ascertain changes they have witnessed. Her analyses thus far reveal observation of local decreases of Dolly Varden trout (*Salvelinus malma*), decreased predictability of travel conditions, and changes in the timing of fish species' runs.

The cloud forests of Haleakalā National Park (Hawaii) might seem like an unusual place to study the impacts of drought, but portions of the park have become drier in recent decades. Shelley Crausbay collected data on hydroclimatic (e.g., precipitation) and ecophysiological (e.g., sap flow) factors in 'Ōhi'a (*Metrosideros polymorpha*),

the primary canopy tree (fig. 2), along an elevational transect. For trees near the ecotone, initial results show rapid declines in sap flow just days after lengthy rains, indicating frequent water stress, despite high average rainfall—up to 6,000 mm (234 in) per year. These data will show how vulnerability to moisture stress varies spatially and will help park managers prioritize investment of resources for addressing endangered and invasive species issues in vulnerable forest areas.

Changes in geographic ranges of species are a key concern for park managers faced with planning for a changing climate. Ailene Kane Ettinger is analyzing effects of climate and interspecific competition on tree growth in Mount Rainier's (Washington) forests by conducting field experiments in plots at multiple elevations (fig. 3). Initial results suggest that, as temperature increases during the 21st century, tree



KATIE A. HOLZER

**Figure 4.** Point Reyes National Seashore coastline; the photo illustrates the vulnerability to erosion of the seashore's communities. From Sarah Olverson Hameed's GMW CCFP project, "Climate Change Implications for Natural Communities: A Management Question at Point Reyes National Seashore." Coinvestigators are Jill H. Baty, Katie A. Holzer, and Angela N. Doerr. All are graduate students at the University of California–Davis.

line conifers will grow faster, but lower-elevation conifers will have mixed responses (Ettinger et al. 2011).

Assessing the vulnerability of coastal environments to sea-level rise is a key challenge for managers of national seashores and preserves. Sarah Olverson Hameed and her fellow graduate students are performing a multifaceted assessment of vulnerability at Point Reyes National Seashore in California (fig. 4). They have combined expert judgments on vulnerability of each seashore community type to climate change with climate, dynamic vegetation, and sea-level rise models to develop a vulnerability assessment tool for vegetation communities in the national seashore. The next step in their research is to evaluate the impact of projected changes on species of interest to seashore managers.

## Summary

The first year of the George Melendez Wright Climate Change Fellowship has enabled student researchers to conduct advanced scientific studies that help answer climate change questions confronting park managers. Preliminary results demonstrate evidence of a wide range of observed changes, and improved understanding of the mechanisms underlying climatic and ecological impacts in national parks. Moreover, the program has already demonstrated value through the leveraging of funds garnered by motivated young investigators from across the country. The final results from the 2010–2011 class are due in September 2011 just as the initial field seasons of the 2011–2012 class are concluding. The George Melendez Wright Climate Change Fellowship demonstrates

one aspect of the National Park Service's tradition of supporting science to inform management challenges in the parks.

## Coda

The fellowship is an annual program. Eleven 2011 fellows were selected in April and are beginning their field research during summer 2011. Research topics are diverse and include analyzing sediment cores to reveal biological responses to past climate change in Olympic (Washington) and Glacier (Montana) national parks; assessing how sensitive different populations of marine invertebrates are to ocean acidification in Hawaii and the Channel Islands in California; and analyzing historical writings, photographs, and other records of plant phenology in Acadia

## *The George Melendez Wright Climate Change Fellowship . . . supports new and innovative research by graduate students on impacts of climate change on protected areas.*

National Park (Maine) over the past 100 years. Projects are being conducted in 16 units of the National Park System, from Acadia to American Samoa, and in six NPS regions. A full list of projects is available at <http://www.nature.nps.gov/climatechange/internshipsresearch.cfm>.

### Acknowledgments

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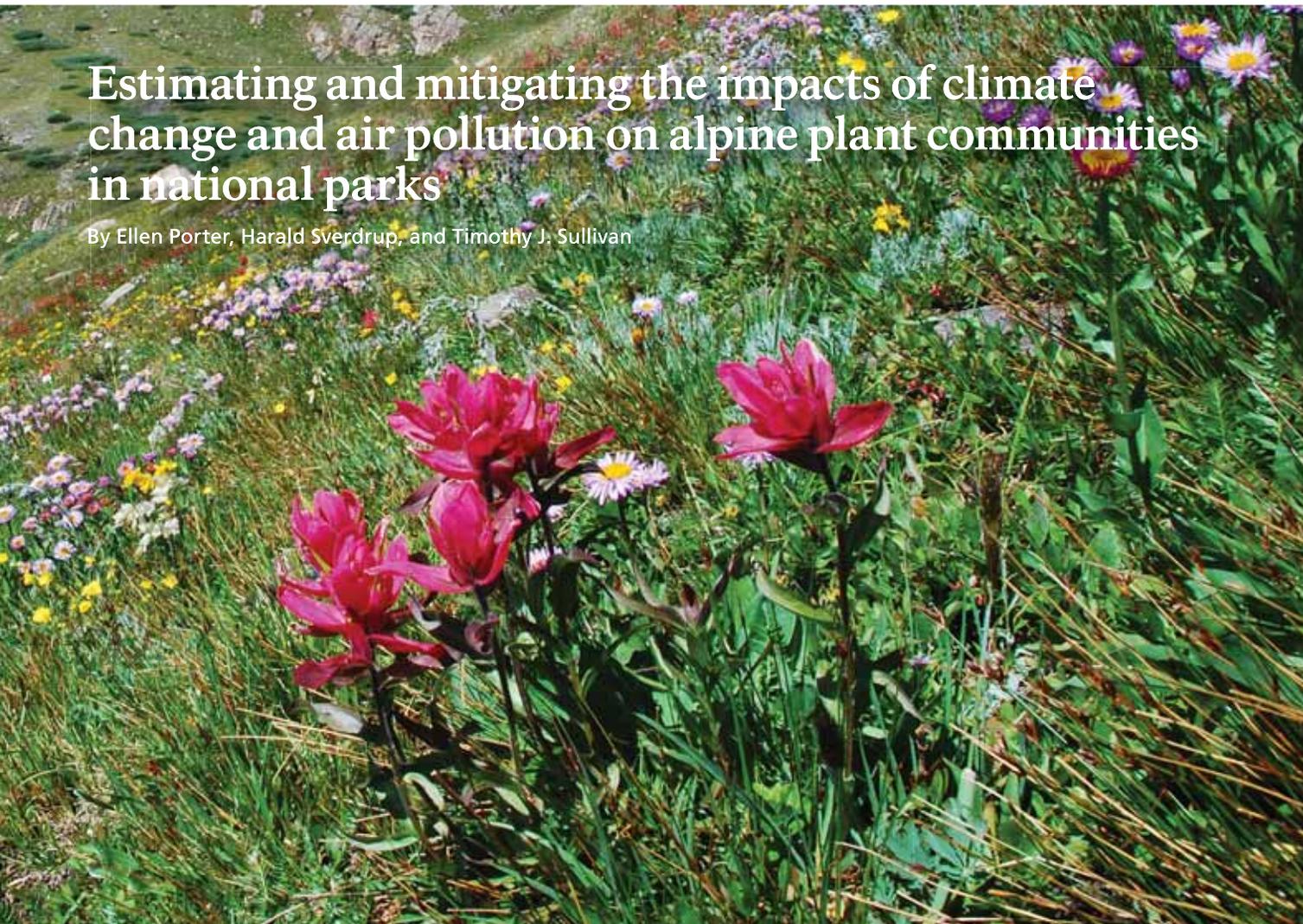
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# Case Studies

## Estimating and mitigating the impacts of climate change and air pollution on alpine plant communities in national parks

By Ellen Porter, Harald Sverdrup, and Timothy J. Sullivan



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**IMAGINE AN ALPINE MEADOW AT THE HEIGHT OF** wildflower season: a tapestry of blue columbines, yellow buttercups, crimson paintbrush, white phlox, and pink bitterroot contrasting with the deep blue sky of the Rocky Mountains (fig. 1). This explosion of color continues to inspire hikers to brave the high winds, low temperatures, and thin air in the high regions of our western national parks during the brief summers that are experienced at those elevations. We know that a changing climate is likely to affect this display (Bowman 2000). A longer growing season and changes in rain and snowfall will alter the alpine environment. Some plants will be displaced and others lost entirely, while some will thrive under new conditions. These changes will occur in addition to those already under way because of air pollution.

Air pollutants containing nitrogen are altering plant communities in many areas of the world because of nitrogen's fertilizing effect (Bobbink et al. 2010). Vehicles, power plants, industry, and agriculture all emit nitrogen that deposits into ecosystems with

**Figure 1.** Alpine meadows and hillsides may look very different in the future as climate change and nitrogen from air pollution cause changes in plant communities.

rain and snow, fertilizing some plants at the expense of others. Alpine plant communities are particularly at risk, having evolved under low-nitrogen conditions (Bowman 2000). When additional nitrogen from air pollution is available, plants with the ability to quickly assimilate it, including some invasive and nonnative species, gain a competitive advantage (Clark et al. 2007). Current levels of nitrogen pollution are sufficient to induce changes in alpine plant communities in and near Rocky Mountain National Park, Colorado (Bowman et al. 2006). But can we anticipate the even greater changes that are likely to occur as nitrogen pollution interacts with climate change? The Air Resources Division of the National Park Service (NPS) has recently collaborated with U.S. and European scientists to apply the innovative environmental effects model ForSAFE-VEG to help estimate future conditions and answer such questions.

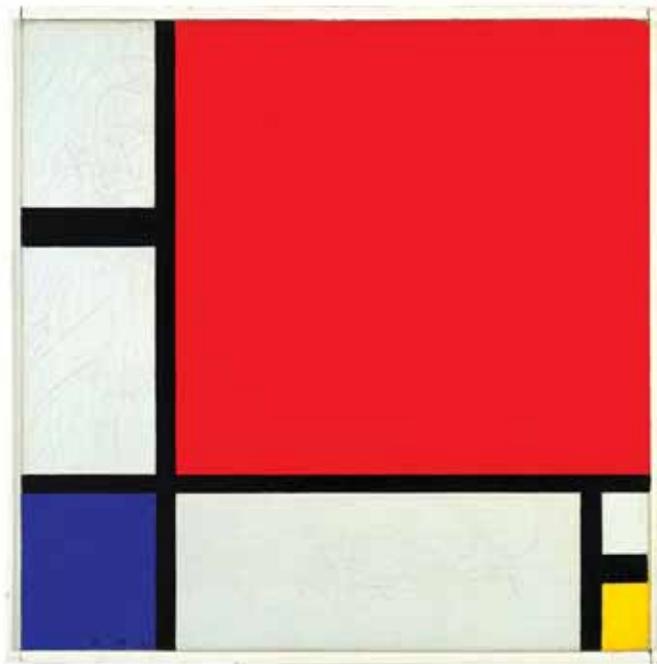
### Abstract

Two of the major stressors affecting plant communities in remote locations are climate change and excess nitrogen input from atmospheric pollution. Both stressors are causing profound changes in ecosystems, and there are strong interactions between plant responses to nitrogen pollution and responses to climate change. Certain native plant communities, notably those found in alpine, desert, and wetland areas, are expected to be very sensitive to both climate change and nitrogen addition. Many plant species in these areas have strict habitat requirements, and as climate change and nitrogen alter physical, hydrological, and chemical conditions, these species are displaced or marginalized. Plant communities located in "edge" or transition zones (e.g., tree line) are expected to be particularly vulnerable. While climate change is disturbing moisture and temperature regimes, nitrogen deposition from air pollution is causing unnatural fertilization (eutrophication) of ecosystems. This enrichment may favor certain species, often invasive weeds, over native plants. Species better able to use nitrogen crowd out native plants adapted to low-nitrogen conditions, making plant communities even more vulnerable to differences in temperature and precipitation expected as a result of climate change. In a workshop held in 2008, National Park Service (NPS) and university alpine plant specialists identified growth requirements of many alpine species in parks, including requirements for light, moisture, temperature, and nitrogen. The information was then used to simulate plant species responses to climate change and nitrogen addition, using the ForSAFE-VEG model. The model was developed in northern Europe to estimate soil chemistry and plant biodiversity responses to climate change and nitrogen pollution. The model is rooted in biogeochemical processes but also includes expert judgment to classify plant species according to their general patterns of response to stress. Based on information from the 2008 workshop, ForSAFE-VEG has recently been applied to a generalized tree line location representing national parks in the central and northern Rocky Mountains. Results of this preliminary model application suggest that ForSAFE-VEG is a useful tool in understanding interactions between nitrogen air pollution and climate change at high-elevation national park locations. For example, reducing nitrogen deposition and its associated stresses may be an effective strategy for increasing the resiliency of alpine plant communities to climate change.

**Key words:** alpine plant, climate change, deposition, model, nitrogen

## Description of model

ForSAFE-VEG is an ecosystem model based on interactions among soil chemistry, hydrology, energy, carbon cycling, nitrogen cycling, tree growth and production, geochemistry, and ground vegetation (Sverdrup et al. 2008). Integral to the model is the ability to account for dynamic competition, that is, to forecast how species will interact under changing physical and chemical



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**Figure 2.** Piet Mondrian's *Composition with Red, Blue and Yellow*, from 1930. The canvas is divided into modular sectors, where colors are confined to a limited space and do not overlap. If one color should expand, it would necessarily replace another color partly or entirely. Similarly, if certain plant species expand their ranges, other species may be displaced.

conditions. ForSAFE-VEG has developed and evolved over 20 years and has been tested extensively against field data in Europe (Sverdrup et al. 2007). A combination of controlled studies and the expert judgment of plant scientists has been used to train the model to simulate plant response to nitrogen and climate change. Each species has an optimal range that is influenced by competition with other plants and may vary over time. The model assumes that, in a given area with limited resources, conditions may be suitable for supporting a variety of species. If one species becomes more prevalent, another species will have to decline. The art of Piet Mondrian has been used to illustrate this principle (Sverdrup et al. 2011). On a Mondrian canvas, colors are confined to a sector and do not overlap (fig. 2). If one color expanded, it would be at the expense of another. Plant species behave similarly. If changing conditions allow a species to expand its coverage, it does so at the expense of other species, which usually have to retreat. ForSAFE-VEG simulates the results of plant and resource interactions. Would the model perform successfully when applied to high-elevation areas in the United States, where alpine plant species are different but have similar growth habits and requirements to their European relatives?

## Science workshop

To begin to answer this question, we held a workshop at the offices of the NPS Air Resources Division in Lakewood, Colorado, in 2008, funded and cosponsored by the division and the Environmental Protection Agency. The workshop included European scientists with expertise in the ForSAFE-VEG model and U.S. scientists from the National Park Service, the U.S. Geological Survey, the USDA Forest Service, universities, and the private sector. The U.S. scientists had extensive experience with alpine and subalpine plants in the Rocky Mountains, the Pacific Northwest, and Alaska and included NPS plant specialists from North Cascades National Park, the Inventory and Monitoring Program office, and the Southwest Alaska Network. We asked them to summarize and evaluate information on plant response to air pollutants and climate in alpine and subalpine ecosystems in the United States. They also developed a preliminary classification for selected U.S. alpine plant species for the parameters required for input to the model. These included average lifespan of the species; requirements for nutrients, water, and light; response to excess nitrogen enrichment; ungulate grazing preference; rooting depth; and effective shading height. The scientists also summarized information about response to climate change and advised us regarding which aspects of climate change (e.g., temperature, precipitation, growing season, and snowpack depth and duration) should be used in the model.

## Proof of concept

We next created a generalized plant community to represent the alpine and subalpine zones of the Rocky Mountains. This community was used to test the feasibility of using ForSAFE-VEG in the United States to simulate effects from climate change and air pollution. We ran the model over the period AD 1750–2400 to represent the range from preindustrial conditions to several hundred years in the future. Plant response data, generated from the workshop and from European studies, were available for 118 species, including grasses, forbs, lichens, mosses, trees, and shrubs. Data used to describe the geology, soils, air pollutant inputs, and climate of the generalized site were based in part on data from five national parks in the Rocky Mountains (Glacier, Yellowstone, Grand Teton, Rocky Mountain, and Great Sand Dunes). Geological data were extracted from spatial data sets on the NPS Data Store (<http://science.nature.nps.gov/nrdata>). Soil physical properties, including pH, percentage of clay, and depth to restricting layer, were derived from the STATSGO database (NRCS 2009). Historical climate data (temperature and precipitation) were obtained from PRISM (PRISM Climate Group at Oregon State University 2006) and were summarized as annual average values

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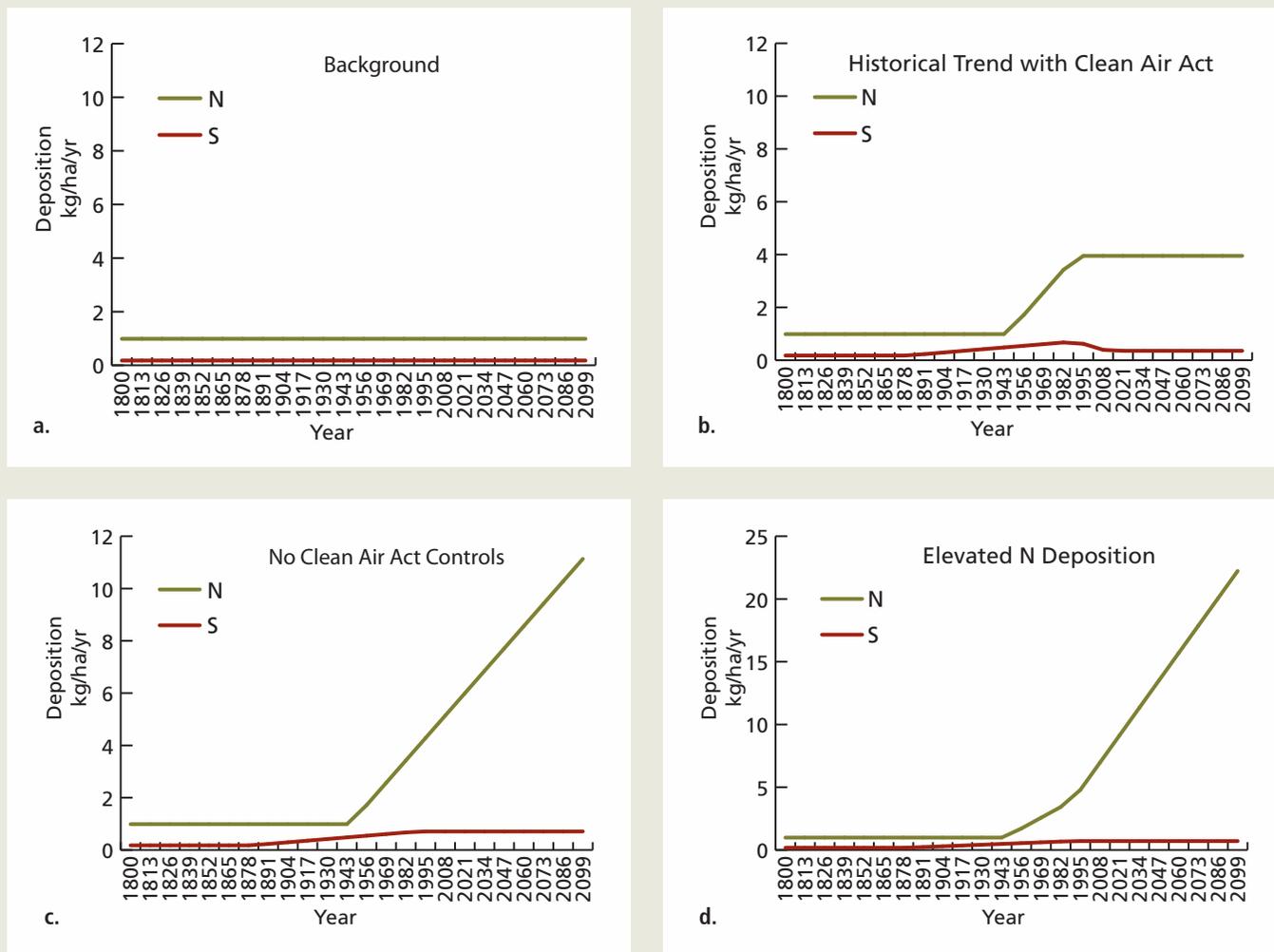
*Integral to the model is the ability to account for dynamic competition, that is, to forecast how species will interact under changing physical and chemical conditions.*

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from 1971 to 2000. Air pollutant deposition was estimated from monitoring and modeling sources. We modeled future scenarios assuming climate change based on the Intergovernmental Panel on Climate Change (IPCC) A2 scenario (Pachauri and Reisinger 2007) and four levels of atmospheric sulfur and nitrogen deposition, ranging from assumed preindustrial background conditions to an absence of sulfur and nitrogen emissions controls with consequent higher levels of sulfur and nitrogen deposition (fig. 3). The A2 climate scenario assumes a relatively higher level of major greenhouse gases than some other IPCC scenarios, but as a result gives more information on impacts than a lower-emissions scenario. The A2 scenario is also being used by the North American Regional Climate Change Assessment Program (NARCCAP).

Although both nitrogen and sulfur deposition were considered in the model, sulfur effects were estimated to be minimal. Rates of sulfur deposition have historically been low in the Rocky Mountains (fig. 3) and are expected to remain relatively low in our modeled scenarios compared to nitrogen deposition because there are few coal-fired power plants, the major sources of sulfur emissions, in the region. Soil acidification, which can be caused by either sulfur or nitrogen deposition, but particularly sulfur deposition because of its strong acidification potential, is not expected unless sulfur deposition significantly increases. The ForSAFE-VEG model results suggest that soil acidification is unlikely to affect alpine plant communities under our expected scenarios. On the other hand, nitrogen emissions sources, including vehicles, industry, power plants, oil and gas production, and agriculture, are numerous in certain areas of the Rocky Mountains and nitrogen deposition is significantly elevated over preindustrial conditions. The model forecasted strong plant community responses to nitrogen deposition and we focus our discussion on those responses.

Figure 4 (page 62) shows estimated changes in plant species composition from AD 1800 to 2200 under the four nitrogen pollution scenarios, assuming the IPCC A2 climate scenario. For the figure, modeled species were sorted into dominant functional plant



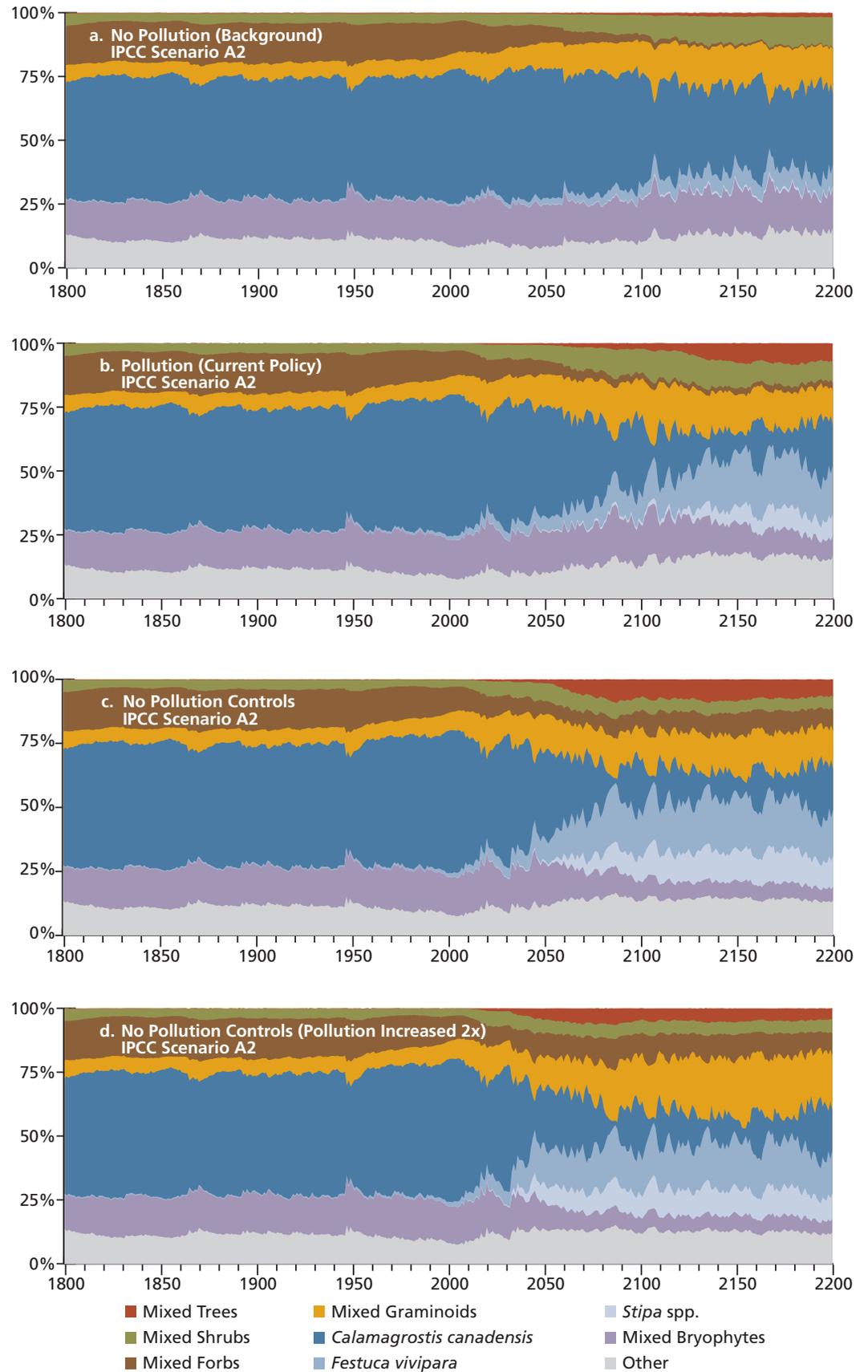
**Figure 3.** Deposition scenarios assumed for this model application: (a) the background scenario, assuming no industrialization of North America; (b) the historical trend with the Clean Air Act, cutting about 50% of sulfur (S) deposition, with minimal change in nitrogen (N) deposition; this scenario approximates recent policy; (c) no Clean Air Act controls on N and S emissions; and (d) future N deposition doubles as compared with scenario C (elevated N deposition). Deposition is assumed to remain constant after 2100.

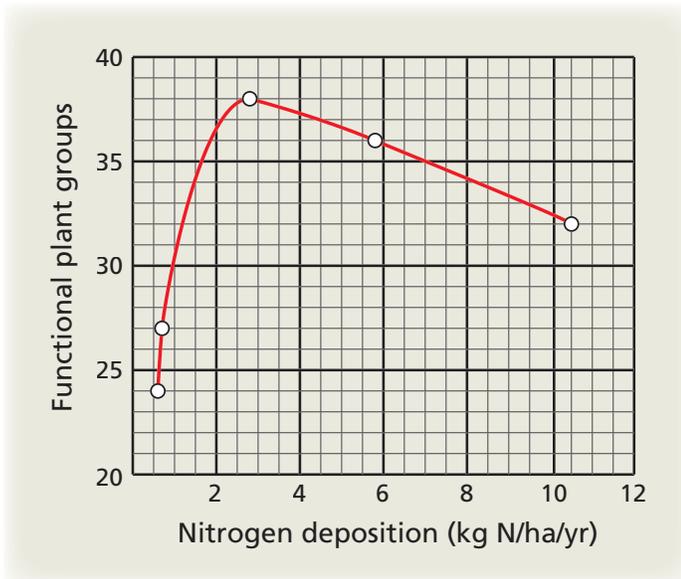
groups, including mosses, grasses, forbs, shrubs, and trees. In addition, several individual species that were estimated to change significantly in abundance over time are depicted. The thickness of a given color band indicates the relative amount of functional plant group or individual species coverage. These thicknesses increase and decrease over time as species and groups become more or less abundant. The site responds with vegetation composition changes as a result of both climate change and nitrogen deposition input. If nitrogen deposition inputs do not change from natural background, but climate does (fig. 4a), ground vegetation is estimated to change significantly. Forbs like *Lupinus nootkatensis* (Nootka lupine) and the grass *Calamagrostis canadensis* (blue-point grass) decrease in percentage of cover; *Festuca vivipara*

(northern fescue) increases. Despite the assumed climate change, the model suggests that without extra nitrogen, the trees (e.g., *Picea* spp.—spruce) will be unable to advance appreciably to the higher alpine areas used in this exercise.

Under atmospheric nitrogen and sulfur deposition levels that reflect recent emissions controls in the United States (fig. 4b), plant species shifts are more pronounced as compared with natural background deposition and climate change. Invasion of trees above the present tree line is simulated to take place in response to nitrogen deposition of about 2.8 kilograms per hectare per year

**Figure 4.** Model simulations for plant species coverage based on the IPCC climate change scenario A2 for this region and (a) background S and N deposition, (b) approximate recent Clean Air Act emissions controls, (c) no Clean Air Act controls, and (d) elevated future atmospheric N deposition.





**Figure 5.** Model results indicate that in low-nitrogen systems like alpine ecosystems, as nitrogen increases, biodiversity increases initially. However, as nitrogen further increases, biodiversity starts to decline.

(kg/ha/yr)<sup>1</sup>, and new species invade the area. For comparison, in 2010 the nitrogen deposition rate in Rocky Mountain National Park was about 4 kg/ha/yr. The model estimated that with climate change and increased nitrogen, mosses like *Pleuzobium schreberi* (Schreber’s moss) will decrease and be partly replaced by grasses or sedges that increase in coverage (*Carex vaginata*—sheathed sedge) or invade (*Poa arctica*—arctic bluegrass).

With further increases in nitrogen deposition, more substantial change in biodiversity is simulated to take place (fig. 4c). This corresponds to a peak deposition of about 5.5 kg N/ha/yr. Model results suggest that the site will be invaded by tree species such as *Picea glauca* and converted from partially open to closed canopy with brushy understory vegetation. Shrubs like *Vaccinium uliginosum* (bog blueberry) decrease, being outcompeted by grasses and herbs. The grasses *Stipa* and *Festuca* are simulated to invade the uplands from lower elevations. *Calamagrostis* is reduced to a marginal grass from having been the most dominant.

If nitrogen inputs increase to higher levels (fig. 4d), the model suggests that larger biodiversity changes will occur. This elevated nitrogen deposition scenario corresponds to a peak deposition of about 10.5 kg N/ha/yr. Under this scenario, the modeled site will become forested, have more *Salix phylicifolia* (willow) undergrowth, and *Lupinus nootkatensis* will be reduced to a marginal species. *Vaccinium uliginosum* is now almost eliminated by grasses

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*A combination of controlled studies and the expert judgment of plant scientists has been used to train the model to simulate plant response to nitrogen and climate change.*

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and herbs, and ferns are firmly established. Many species prevalent under background deposition will have been replaced totally; many new plant species will have invaded. Simulated biodiversity will have changed considerably.

The model allows us to estimate the “critical load,” defined as the amount of deposition below which some specified harmful change is not expected to occur to an ecosystem or to some attribute of an ecosystem (Porter et al. 2005). Based on the model results, a nitrogen critical load in the range of 1 to 2 kg/ha/yr would protect against a change of 5% in plant species coverage, as compared with natural background deposition.

The model also allows us to look at changes in biodiversity, defined as the number of functional plant groups present. Figure 5 shows that under very low nitrogen conditions, biodiversity is low at our hypothetical site. As nitrogen increases somewhat, biodiversity increases because nitrogen is a nutrient. But as nitrogen increases further, biodiversity starts decreasing as certain species are favored while others are eliminated, a pattern seen in certain other ecosystems (Clark et al. 2007).

Thus, model results suggest that this hypothetical ecosystem is vulnerable and prone to significant losses in plant biodiversity with warming climate and increasing atmospheric nitrogen deposition. The outputs show a response time that is very long, in the range of a century or more. Comparable results were found in Europe by Sverdrup et al. (2007) and Belyazid et al. (2011). This suggests that air quality management decisions made today will have ramifications far into the future. Reducing nitrogen deposition should be an important consideration when planning for climate change.

<sup>1</sup>One kilogram per hectare is approximately equal to 0.9 pound per acre.

## Conclusion

The results of preliminary ForSAFE-VEG modeling for a synthetic tree line site in the Rocky Mountains region are encouraging. The model appears to be a feasible tool for evaluating the interactions of climate change with air pollution, specifically deposition of atmospheric nitrogen. The model estimated the critical loading of nitrogen deposition above which plant biodiversity decreases. This critical load may now be exceeded at some places in the region. The results suggest that both climate change and nitrogen pollution can significantly affect alpine plant community composition and diversity. Reducing nitrogen pollution and deposition will reduce overall impacts of climate change on these ecosystems.

## Next steps

A synthetic site was used for this test of the ForSAFE-VEG model. The NPS Air Resources Division plans to apply the model to data specific to a park ecosystem, possibly Rocky Mountain National Park. The model may prove to be an important tool in forecasting and ultimately mitigating the impacts of climate change.

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# Parks use phenology to improve management and communicate climate change

By Abraham Miller-Rushing, Angela Evenden, John Gross, Brian Mitchell, and Susan Sachs

**R**APID CLIMATE CHANGE—SUCH AS RECENT CHANGES in climate that are occurring more rapidly than at any time since the last glacial maximum—presents two particularly formidable challenges for national parks and society in general. First, we must improve our understanding of the effects of climate change and how to manage them. Second, we must communicate the science of climate change in a concrete, noncontroversial (or minimally controversial) way that promotes understanding and action. In the National Park Service (NPS), many efforts are under way to address these two challenges (<http://www.nps.gov/climatechange>). Here, we describe one promising approach that addresses both challenges simultaneously: studying climate-driven changes in phenology—the timing of seasonal biological events, such as flowering and migrations.

Phenology has played an important role in the lives of people, plants, and animals through history. Human subsistence has depended on knowing when food plants are available and when game species arrive or depart on migrations. Much of ecological theory and many of our management practices recognized this, but assumed that phenology was relatively stable from one year to the next, in part because climate, which drives the timing of many phenological events, was long thought to be fairly stable, or “stationary” (Milly et al. 2008).

In a period of rapid climate change, though, understanding phenology becomes even more important. Almost every ecological relationship and process—including predator-prey and plant-pollinator interactions, the spread of disease, pest outbreaks, and water and carbon cycling—depends on the timing of phenological events (Forrest and Miller-Rushing 2010). As climatic conditions change, phenology changes, and so do these ecological relationships and processes. These shifts are further complicated because the phenologies of different species change at different rates and in different directions, some occurring earlier, others later (Sherry et al. 2007; Thackeray et al. 2010). In some cases this may lead to mismatches, as has occurred in parts of Europe where pied flycatchers (*Ficedula hypoleuca*) are now breeding too late relative to when their primary food source, winter moth caterpillars, is available; where this mismatch is most severe, populations of pied flycatchers are declining by up to 90% (Both et al. 2006). Changes in phenology also vary across space, as is

## Abstract

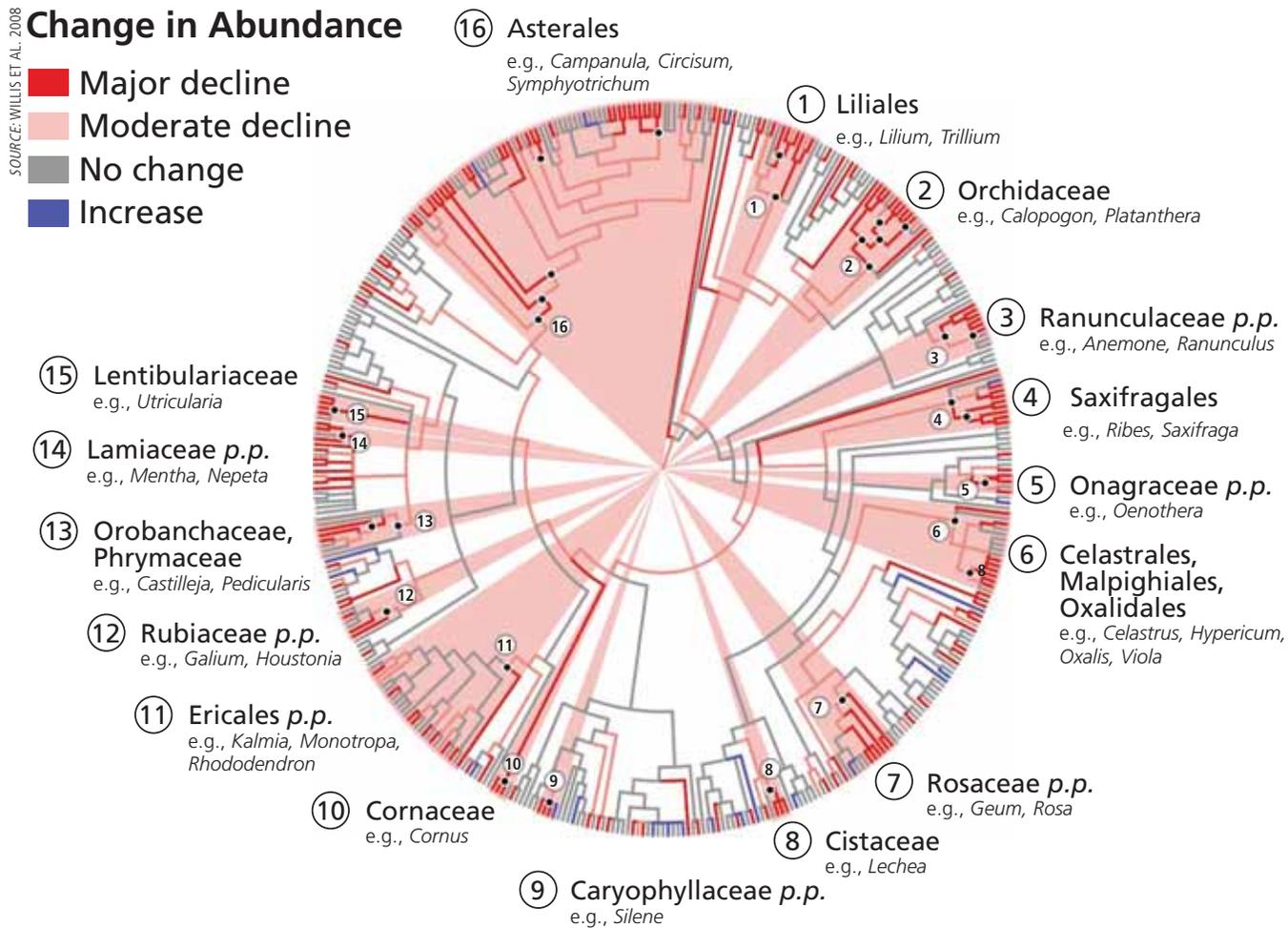
Climate change presents the dual challenges of (1) understanding its effects and how to manage them and (2) communicating climate change science to promote understanding and action. Here we describe one approach to addressing those challenges: studying climate-driven changes in phenology—the timing of seasonal biological events, such as flowering and migrations. Phenology is critical to people and the functioning of ecosystems, and it is changing wherever climate is changing. Thus it provides information for managers and local examples of effects of climate change that are relevant to park visitors and the communities surrounding parks. Parks, Research Learning Centers, Inventory and Monitoring Networks, and Cooperative Ecosystem Studies Units across the country are piloting methods, such as citizen science and remote sensing, for monitoring phenology and using the results to inform science, management, and education. These activities are gaining momentum and are poised to make significant contributions to our understanding of the effects of climate change and how best to communicate climate change science to the public.

## Key words

citizen science, climate change, Cooperative Ecosystem Studies Units, Inventory and Monitoring Networks, phenology monitoring, Research Learning Centers

evident in the earlier-than-average spring green-up and flowering of most plants in the northern United States, but later in southern regions (Zhang et al. 2007; Von Holle et al. 2010). Right now we are ill-equipped to predict the impacts of phenological changes on species and ecosystems because of a dearth of data describing the phenology of most species and the role of timing in regulating species interactions and ecological processes.

In addition to its role in ecosystem functions, phenology provides one of the most fundamental ways people relate to nature. Phenological events mark the changing of seasons: the emergence of leaves and butterflies and the sounds and activities of birds, frogs, and other animals herald the arrival of spring; fall foliage and crop harvest mark the onset of autumn and winter in much of the country. Because phenology is tightly coupled with climate and is changing wherever climate is changing, it provides a way that people can “see” climate change and its impacts wherever they are.



**Figure 1.** Composite phylogeny of 429 flowering plant species from the flora of Concord, Massachusetts, depicting changes in abundance from 1900 to 2007. Groups with first flowering dates that did not track changes in spring temperatures tended to decline in abundance. Branch color indicates change in abundance. Clades (i.e., groups of species that share a common ancestor) exhibiting declines of 50% or more are indicated with black dots. Each of the most inclusive clades exhibiting these severe declines is indicated in pink and referenced numerically to its clade name. These clades include some of the most charismatic wildflower species in New England, such as anemones and buttercups (Ranunculaceae *p.p.* [*pro parte* or in part, that is, only part of this taxonomic group has declined]); asters, campanulas, goldenrods, pussytoes, and thistles (Asterales); bedstraws and bluets (Rubiaceae *p.p.*); bladderworts (Lentibulariaceae); dogwoods (Cornaceae); lilies (Liliales); louseworts and Indian paintbrushes (Orobanchaceae); mints (Lamiaceae *p.p.*); orchids (Orchidaceae); primroses (Onagraceae *p.p.*); roses (Rosaceae *p.p.*); saxifrages (Saxifragales); Indian pipes (Ericales *p.p.*); and St. John's worts and violets (Malpighiales).

SOURCE: WILLIS ET AL. 2008

## Phenology and national parks

Climate-driven changes in phenology are highly consequential to national parks because they are linked to important processes such as outbreaks of forest pests and increases in fire severity in the West (Hicke et al. 2006; Westerling et al. 2006), declines in and disappearance of wildflower populations in the Northeast (Willis et al. 2008) (fig. 1), and the spread of invasive species throughout the country (Willis et al. 2010). Timing of festivals tied to phenological events, such as flower displays or migrations, is changing because of both global climate change and urbanization (Aono and Kazui 2008; Primack et al. 2009). In Boston, for

example, the annual lilac festival at the Arnold Arboretum now occurs three weeks earlier than it did 90 years ago (Loth 2011). Visitor seasons will likely shift as timing of the growing season shifts, lengthening in some areas and shortening in others. Parks can play a key role in understanding the causes and consequences of these changes: they contain some of our country's most valued and unaltered landscapes and are distributed along ecological, climatological, and geographical gradients, making them ideal locations for investigating ecological responses to climate change.

The National Park Service is taking a leadership role in the effort to monitor phenology and improve our understanding of the

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**Figure 2.** Examples of several methods for collecting phenology data: volunteers, cameras, and audio recorders. The images were taken at (a) Boston Harbor Islands National Recreation Area, (b) the Harvard Forest Environmental Measurement Site tower site in the PhenoCam network (Richardson et al. 2009), and (c) Marsh-Billings-Rockefeller National Historical Park in Vermont.

effects that phenological changes will have on plants, animals, and people. Our strategy is three-pronged: (1) observe phenology in the field, (2) share and analyze data and information to increase their value, and (3) communicate with and engage the public. We are just beginning our work in these areas, but it is rapidly progressing.

There are a diversity of initiatives and approaches to monitoring phenology throughout the system of national parks, with different goals, audiences, and target species. To emphasize the range of activities and how they meet parks' needs, we briefly describe three NPS phenology projects and use them as examples in subsequent sections: (1) monitoring across the Northeast Temperate Inventory and Monitoring Network (NETN), including the collaboration of member parks and the Schoodic Education and Research Center at Acadia National Park, Maine; (2) the California Phenology Project (CPP), a collaboration among 19 parks, two Research Learning Centers (RLCs), five Inventory and Monitoring (I&M) Networks, and the Californian Cooperative Ecosystem Studies Unit (CESU); and (3) monitoring at Great Smoky Mountains National Park and its associated Appalachian Highlands Science Learning Center. Each of these projects involves extensive collaboration with other agencies, nongovernmental organizations, and academic institutions.

## Making observations on the ground

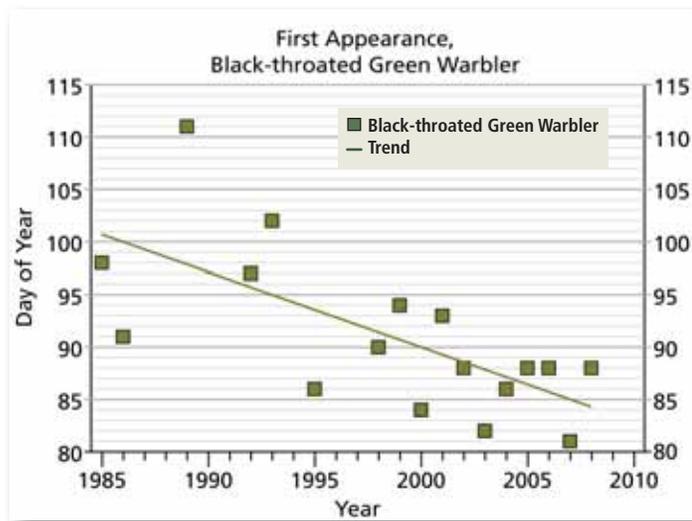
Most current NPS phenology monitoring efforts rely on volunteers to make field observations. This citizen science approach works well because most people already observe phenology every day—they just do not write down their observations. Therefore, the oversimplified keys to monitoring phenology on the ground are to identify monitoring goals, recruit individuals to observe the phenological phases of interest—say, leaf expansion, birdcalls, or a bee visiting a flower—and have participants record their observations in a standard way.

To help with standardization, the National Park Service is working with the USA National Phenology Network (USA-NPN; see sidebar) and many other organizations and individuals to develop monitoring standards and online tools for training, data submission, reporting, mapping, and graphing. The standards for monitoring ensure that everyone is making the same basic observations, which facilitates aggregation and integration of observations across sites and species while providing flexibility so monitoring efforts can pursue different goals.

For example, NETN monitoring projects began with a focus on science, addressing questions such as how phenology is related to invasiveness, water relations, and other natural resource issues. The project in Great Smoky Mountains National Park began with a focus on education, giving participants a way to engage in climate change science and see local impacts of climate change. The California Phenology Project blends science and education objectives related to understanding resource response to climate change. No matter the initial impetus, all three programs are moving toward having equally strong science *and* education components.

Additionally, in the NETN and CPP monitoring efforts, different parks are testing and implementing different approaches. Individual parks rely on various mixes of trained volunteers, staff, and automated cameras and audio recorders to make field observations (fig. 2). The mix each park uses depends on the monitoring goals and capacity of their volunteer community and park staff. Phenology monitoring projects under way in the National Park Service are actively testing these and other approaches to find which ones best achieve their science and education goals.

In addition to collecting field observations, parks are identifying historical data sets that can help them increase the length of their monitoring records. For example, the Great Smoky Mountains



**Figure 3.** Changes in the first appearance of black-throated green warblers in Walker Valley, Tennessee, Great Smoky Mountains National Park. Trend =  $-0.7$  days/year.

DATA SOURCE: GREAT SMOKY MOUNTAINS INSTITUTE AT TREMONT

Institute at Tremont, a nonprofit environmental education center, is analyzing and building on more than 30 years of phenology data (fig. 3). Many scientists, amateur naturalists, gardeners, and others habitually record their observations of flowers, fruits, birds, butterflies, and other phenological phases and events. Data sets like these have turned up across the country, often in unexpected places, and have led to valuable scientific insights (Ledneva et al. 2004; Miller-Rushing et al. 2006; MacMynowski and Root 2007; Crimmins et al. 2010) (fig. 4). Many parks almost certainly have undiscovered phenology data sets in their collections or in collections or attics of organizations and individuals in surrounding communities. These records can help scientists and resource managers understand local impacts of climate change and can be used by interpreters and educators to communicate those impacts to the public.

Efforts to analyze all of these historical data and new observations to inform park management are just getting under way. In the Southwest, phenology observations are being used to time the treatment of invasive species, such as buffelgrass (*Pennisetum ciliare*). In other areas, researchers are attempting to identify temporal mismatches that may be occurring between interacting species and are exploring the relationships between phenology and pest outbreaks, streamflow, fire, and carbon sequestration. Data collected in parks are also feeding into national efforts to model future changes so that we can better anticipate the consequences of phenological changes to come.



ANONYMOUS



RICHARD PRIMACK/BOSTON UNIVERSITY

**Figure 4.** Photographs showing changes in timing of leaf-out at Lowell Cemetery in Lowell, Massachusetts. Trees lack leaves in the 1868 photograph. The same trees were fully leafed in 2005. Both photographs were taken 30 May. SOURCE: MILLER-RUSHING ET AL. 2006.

## Sharing and communicating

To be sure, the National Park Service is not alone in its effort to monitor phenology and to understand the causes and consequences of phenological changes. It coordinates with the USA National Phenology Network and its many partners, including a wide variety of government agencies, nongovernmental organizations, academic institutions, and individuals, which dramatically increases the power of our work. As part of a community, we have access to data that can greatly increase the density of observations in a particular area and that provide a regional context that would otherwise be missing. Collaboration helps improve our monitoring and education techniques and facilitates rapid adoption of innovations developed by our partners. Our work reaches a far wider audience through our collaborators, whether that audience is researchers, managers, educators, or the public.

*Because of the close link between phenology and climate, phenological changes are occurring virtually everywhere and provide concrete examples where other impacts of climate change may be difficult to see or describe.*

Collaboration *within* the Park Service also improves the ability of our phenology monitoring projects to achieve their goals. Because of the interdisciplinary nature of phenology monitoring—its implications for science, education, and management of a range of natural resources, such as air, water, and wildlife—collaborations across park divisions, RLCs, I&M Networks, and CESUs are necessary (fig. 5). To enable this collaboration and communication, we organized a special session at the biannual meeting of the George Wright Society in March 2011, initiated an e-mail list focused on phenology in the National Park Service (<http://webmail.itc.nps.gov/mailman/listinfo/npsphenofans>), and established a Web site with information about NPS activities related to phenology ([www.usanpn.org/nps](http://www.usanpn.org/nps)). Additionally, each of the three projects in California, the Northeast, and Great Smoky Mountains National Park has formed committees and working groups to deal with particular issues, such as identifying indicator species, developing training materials, managing data, and sharing educational resources. The products of these committees and working groups are, in turn, feeding into the development of standard operating procedures.

## Engaging the public

Phenology is a particularly effective means to communicate climate change because it is so strongly based on place. Local phenological changes connect climate change to people's day-to-day lives and to the places they live or recreate. Local phenological changes are not theoretical or distant but are “here and now,” and are easy for anyone to observe. Because of the close link between phenology and climate, phenological changes are occurring virtually everywhere and provide concrete examples where other impacts of climate change may be difficult to see or describe.

Observing phenology and actively participating in national-scale climate change research give participants firsthand experience in how scientific research is conducted and why climate science



U.S. FISH AND WILDLIFE SERVICE/KATE ESCHBACH

**Figure 5.** Phenology training at Santa Monica Mountains National Recreation Area. This training was a part of the California Phenology Project, which involves collaborations among parks, RLCs, I&M networks, the Californian CESU, and area universities.

matters at the local level. This experience can enhance participants' understanding of science content and process, encourage them to see themselves as science learners, and may encourage some to take action to promote climate change mitigation and adaptation (Weber 2006; Bonney et al. 2009). Furthermore, volunteers who assist in data collection in parks can continue their monitoring at home through many citizen science programs (see [usanpn.org](http://usanpn.org) or [citizenscience.org](http://citizenscience.org)). Data collected by volunteer observers are not superfluous but rather constitute valuable scientific observations that have led to important insights (e.g., Torti and Dunn 2005; Wolfe et al. 2005; Crimmins et al. 2010).

An important way for local community members to participate and contribute is by identifying historical phenology data. Acadia National Park recently hosted an event asking park staff and community members to share observations of local phenological events—everything from deer breeding to cruise ship seasons. In the course of discussion, people identified many “shoebox” data sets stored on bookshelves or in attics or photo albums. This engages people in the process of science, connects them with our country's heritage of natural history observation, and yields valuable data for science, management, and education.

## The future

Monitoring phenology in parks has the potential to advance many science and education goals of the National Park Service and the United States more broadly. Phenological monitoring can contribute to priorities like getting youth outside, engaging local communities, building scientific literacy, preserving America's great outdoors, and advancing climate change science. Phenol-

ogy monitoring complements ongoing efforts in the National Park Service, such as the Climate Change Response Program, the Climate Change Interpretive Competency Subject Matter Expert Group, the Place-based and Climate Change Education Partnership, and monitoring activities in the Inventory and Monitoring Program focused on climate change.

Of course, using phenology observations to achieve meaningful science and education objectives can be challenging, and requires communicating across disciplines, acquiring funding and other support, identifying leaders and partners, and identifying and im-

plementing the best approaches. The National Park Service and the broader phenology monitoring community are well poised to address these challenges. Costs of volunteer-based monitoring are low relative to the benefits to parks and park visitors. In an era of climate change, phenology monitoring makes important contributions to identifying and understanding environmental changes and to engaging and educating park staff and visitors.

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## Standards and tools for using phenology in science, management, and education

By Carolyn Enquist and Abraham Miller-Rushing

**THE USA NATIONAL PHENOLOGY NETWORK (USA-NPN)**, established in 2007, is a national science and monitoring initiative focused on using phenology to understand how plants, animals, and landscapes respond to environmental variability and climate change. The network is collaborative, involving the contributions of government agencies, tribes, nongovernmental organizations, academic institutions, and individuals across the country.

The national coordinating office (NCO) of USA-NPN maintains an information management system for phenology-related data and information, develops and implements standardized phenology monitoring protocols, facilitates research and the development of decision support tools for resource managers, and promotes education and public engagement activities related to phenology and climate change. In addition the coordinating office facilitates partnerships across organizations, disciplines, and regions.

The tools and services provided by the national coordinating office are rapidly expanding, as is the field of phenology as a whole. Here we list a few of the new tools and services the network provides:

- *Nature's Notebook*, an online Web interface that allows participants to submit phenological observations following peer-reviewed, standardized methods.
- Tools for visualizing or downloading data from Nature's Notebook that can be customized to facilitate local phenology monitoring projects, such as those organized by parks and Inventory and Monitoring Networks, eliminating the need for local projects to create their own databases and other cyberinfrastructure.

- A list of phenology-related citizen science projects.
- Tools for running phenology trainings and workshops.
- A clearinghouse of educational resources and a guide to phenology monitoring for students, teachers, and families.
- An online registry of historical data sets. You can submit records of data sets or search the registry to find data sets to use for research or educational applications.
- *Coming soon:* Peer-reviewed documentation of standard phenology monitoring methods designed to enable collection of sampling intensity and absence data for both plants and animals (i.e., standard operating procedures and protocols) is anticipated in 2012.
- *Next steps:* Development of phenology-based forecast and early warning systems for anticipating the ecological effects of changes in streamflow, drought, temperature and precipitation extremes, and wildfire frequency.

For more information about the USA-NPN, go to [www.usanpn.org](http://www.usanpn.org). For National Park Service-specific activities, go to [www.usanpn.org/nps](http://www.usanpn.org/nps).

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## Hummingbird monitoring in Colorado Plateau parks

By Jean Palumbo



Sarah Haas, wildlife biologist for Bryce Canyon National Park, observes while Adam Hutchins, Dixie National Forest wildlife technician, bands a hummingbird.

NPS/JEAN PALUMBO, SOUTHERN COLORADO PLATEAU NETWORK

**HUMMINGBIRDS HAVE ONE OF THE HIGHEST METABOLIC** rates of any animal (Hargrove 2005). When you consider their small size and the long migrations of many species, hummingbirds quite possibly could serve as an early indicator of the cascading effects of a warming climate in the western United States. When the timing of flowering for nectar-producing plants does not coincide with their daily energy needs, hummingbird populations may decline. And since hummingbirds are pollinators, a decline in their numbers could cause a decline in fruit production for the plants they pollinate (Allen-Wardell 1998). This, in turn, may adversely affect populations of organisms that feed on fruit, such as other bird and animal species, including invertebrates and microbes.

“It’s all about phenology,” says Larry Norris, NPS southwest research coordinator for the Desert Southwest Cooperative Ecosystem Studies Unit (CESU). “When do the plants that hummingbirds feed on bloom? When do the midges and gnats that they eat hatch?” To discover how phenology—the timing of periodic biological phenomena—affects hummingbirds, the CESU provided funding in 2003 that was critical in establishing the

Hummingbird Monitoring Network (HMN), which is run by executive director Susan Wethington and headquartered in Patagonia, Arizona. This helped to start up monitoring sites in Arizona’s Chiricahua National Monument, Coronado National Memorial, and Tumacacori National Historical Park, and marked the beginning of hummingbird monitoring on the Colorado Plateau.

### Monitoring

Long-term monitoring of hummingbirds is a tool that can help us determine the effects of climate change, not only on hummingbirds but also on the ecosystems they inhabit (Armstrong 2007). “If we detect a decline in hummingbird populations,” says George San Miguel, natural resource manager at Mesa Verde National Park, Colorado, “that may be a clue that something is going on in their breeding grounds, along their migration route, or in their wintering range. And that could lead us to identify factors in the environment that are in decline.” San Miguel has been working with the Hummingbird Monitoring Network in Mesa Verde since 2006. He helped recruit a group of volunteers who underwent rigorous training to learn how to band hummingbirds and are the core of the park’s monitoring team (figs. 1, 2, and 3). This group

NPS/JEAN PALUMBO, SOUTHERN COLORADO PLATEAU NETWORK (2)



**Figure 1.** To capture hummingbirds the monitoring crew at Mesa Verde National Park uses a Hall trap (a), which covers a hummingbird feeder on a stand. When one or more hummingbirds are at the feeder, the trapper releases the string that holds the trap and the trap drops, capturing the feeding hummingbirds.



**Figure 2.** Hummingbird bander Lynn Udick of the Hummingbird Monitoring Network takes tail feather measurements at Mesa Verde.

NATALIE MELASCHENKO, SOUTHERN COLORADO PLATEAU NETWORK



**Figure 3.** A volunteer with the Hummingbird Monitoring Network releases a banded male broad-tailed hummingbird.

of citizen scientists also fulfills a public outreach function, educating their friends, neighbors, and others in the birding community about their work, and recruiting new volunteers in the process.

In Utah a collaborative, interagency effort has coalesced around hummingbird monitoring. In 2010 Sarah Haas, biologist for Bryce Canyon National Park, teamed up with Lisa Young, biologist for the Dixie National Forest, and Terry Tolbert, biologist for the Grand Staircase–Escalante National Monument, to begin hummingbird monitoring in southwestern Utah. All three underwent training with the Hummingbird Monitoring Network and established three sites at different elevations and in different vegetation types: ponderosa pine forest at Bryce Canyon (see photo, previous page), desert scrub at the Escalante Visitor Center, and the riparian area at Calf Creek campground in Dixie National Forest. Monitoring across the landscape and in different ecosystems will present the broader picture of hummingbird populations in this part of Utah.

Cooperation among the agencies encourages these three biologists to exchange ideas, work together on solving problems, and come up with strategies that will help species cope with climate change. For example, Tolbert is creating a dichotomous key for pollen collected from nectar plants on the monument. Using this key and pollen gathered from the beaks and heads of hummingbirds, he will be able to identify the plants that hummingbirds rely on. Based on this information, managers could adopt postfire restoration strategies that would improve habitat for hummingbirds by including seeds of these plants in reseeding mixes.

Recapture data from HMN monitoring have shed light on hummingbird migration routes, indicating that Anna's hummingbirds may be migrating through southeastern Arizona to southern

California. Broad-tailed hummingbirds banded in the Chiricahua Mountains of southeastern Arizona have been recaptured in Rocky Mountain National Park, Colorado, suggesting the Rocky Mountain Flyway as the migration route for these tiny birds. As new monitoring sites come online and new collaborative efforts are formed, the capacity for information gathering and study increases. Earlier this year the Hummingbird Monitoring Network and Stony Brook University in New York obtained a grant from the National Aeronautics and Space Administration to study how hummingbirds respond to climate change. The Hummingbird Monitoring Network will work with USA-National Phenology Network to establish monitoring of hummingbird nectar plant phenology as part of this study.

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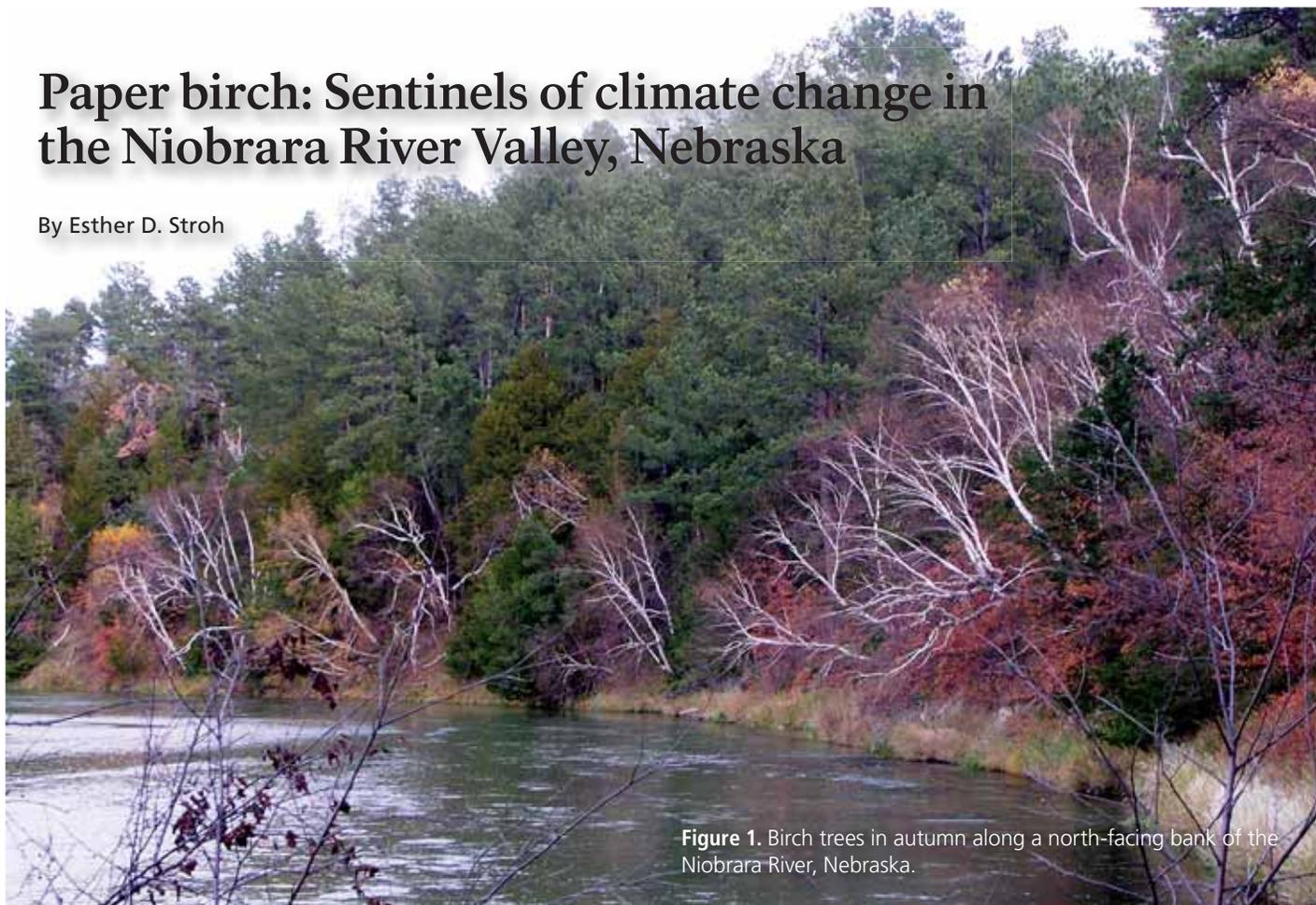
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# Research Reports

## Paper birch: Sentinels of climate change in the Niobrara River Valley, Nebraska

By Esther D. Stroh



USG/ESTHER STROH

**Figure 1.** Birch trees in autumn along a north-facing bank of the Niobrara River, Nebraska.

**T**HE NIOBRARA NATIONAL SCENIC River, in north-central Nebraska, is known for encompassing a wide mix of species at or beyond their typical geographic ranges. Plants representative of eastern and western forests and several prairie types are maintained by localized microclimates that change abruptly with differences in topography, soils, slope, and moisture (Kaul et al. 1988). For example, paper birch trees (*Betula papyrifera* Marsh) can be found on north-facing slopes on the south bank of the river and in small protected canyons on both the north and south sides of the river (fig. 1). Paper birch is typically an important component of boreal forests, but here in the middle of the Great Plains, remnant populations remind us that the area once supported a very different mix of vegetation under different climatic regimes. Birch populations are believed to have persisted in the Niobrara River Valley since the end of the Wisconsin glaciation, when conditions supported boreal species (Wright 1970).

Paper birch rarely occurs naturally where average July temperatures exceed 21°C (70°F; USDA 1965). The average July temperature in Valentine, Nebraska, 4 km (2.5 mi) from the nearest birch trees,

### Abstract

The Niobrara River Valley in the northern Great Plains supports scattered stands of paper birch (*Betula papyrifera* Marsh), a species more typical of boreal forests. These birch stands are considered to be relictual populations that have persisted since the end of the Wisconsin glaciation. Localized summer microclimates have likely facilitated the persistence of birch populations in a region otherwise unsuitable for the species. Dieback of canopy-sized birch has been observed throughout the valley in recent years, although no onset dates are documented. Changes in spring weather patterns may be causing rootlet injury so that trees die in spite of the still-cool summer microclimates. Current weather patterns, combined with little evidence of recruitment of young birch and great geographic distances from potential immigrant sources, make the future persistence of birch in the Niobrara River Valley stands uncertain.

### Key words

*Betula papyrifera*, climate change, crown dieback, Niobrara National Scenic River, paper birch, relict plant populations

is 23°C (73°F; National Weather Service 2008). However, relict populations can persist for thousands of years outside of their typical range in sites with favorable microclimates (Stebbins and Major 1965). Presumably, microclimates in birch sites have maintained birch populations for roughly 10,000 years. However, resource managers have observed many dead or dying birch trees in recent years (fig. 2); in some sites, nearly all trees have died. Why are they dying now after such a long presence in the Niobrara Valley?

## Background

Widespread dieback of paper birch has been observed in other areas, and these events have been associated with atypical weather patterns. For example, from 1935 to 1945 in Maine and Nova Scotia, 67% of paper and yellow birch (*Betula alleghaniensis* Britt) died and 15% of remaining trees were dying (Nash and Duda 1951). Later, this dieback event was attributed to low winter temperatures, late spring freezes, years with below-average winter snow cover, combined with below-average temperatures and years with above-average spring temperatures (Greenidge 1953; Braathe 1995). Plant developmental stages such as flowering and bud burst typically occur after a certain amount of heat accumulation in the spring, also known as growing degree days (GDD). Some crops and native plants can be injured if a hard freeze occurs after plants have reached certain early growth stages. Crown dieback in birch is an expression of rootlet mortality, and shallow birch roots can be injured by thawing and then refreezing. Specifically, a spring thaw-freeze cycle of March growing degree days greater than 50°C (equivalent to GDD greater than 90°F), followed by April or May temperatures below -4°C (25°F), can induce root injury and subsequent crown dieback in paper birch (Braathe 1995). Damaged birch roots are less able to provide sufficient pressure to refill the stem xylem with sap in the spring, and the tree begins to die from the tips of the branches back to the main stem. These are the symptoms presented by the Niobrara birch trees.

## Methods

Could atypical weather patterns in recent years explain dieback of the Niobrara birch trees? We used data loggers to record air temperature every half hour from June 2005 through October 2007 in 12 birch stands and compared these data against concurrent and historical data from the National Weather Service station in Valentine, Nebraska. We also assessed percentage of canopy dieback of 248 birch trees growing in these and 13 additional sites along approximately 68 km (42 mi) of the Niobrara River (fig. 3). Most sites were located on the south bank of the river on north-facing slopes or in north-facing canyons near the riverbank; a

USGS PHOTO



**Figure 2.** Dead and dying stems of paper birch amid apparently healthy stems.

few stands were on the north side of the river in protected small canyons. Our results are reported in Stroh and Miller (2009).

## Findings and discussion

We used the entire period of record available from the Valentine weather station (1948–2007) and simply divided it into two 30-year periods. We found that frequency of thaw-freeze conditions capable of inducing crown dieback increased significantly from 1978 to 2007 (the second half of the period of record) compared with 1948 to 1976, the first half of the period of record. From 1948 to 1976, 7 out of 30 years (23%) met the combination of a warm March followed by a cold snap in April or May; from 1977 to 2007, 15 out of 30 years (50%) met these conditions, a significant difference in proportion ( $z = -2.179$ ,  $p = 0.029$ ; Stroh and Miller 2009). Importantly, average April and May minimum temperatures in both periods were identical; increasing frequency of warm spells in March contributes to increased frequency of conditions that can induce rootlet injury in birch trees.

We also found microclimate differences among types of birch sites and among birch sites as compared with the Valentine weather station. During the crucial spring months, maximum temperatures were higher and minimum temperatures were lower in birch sites on the north side of the river than in those on the south side.

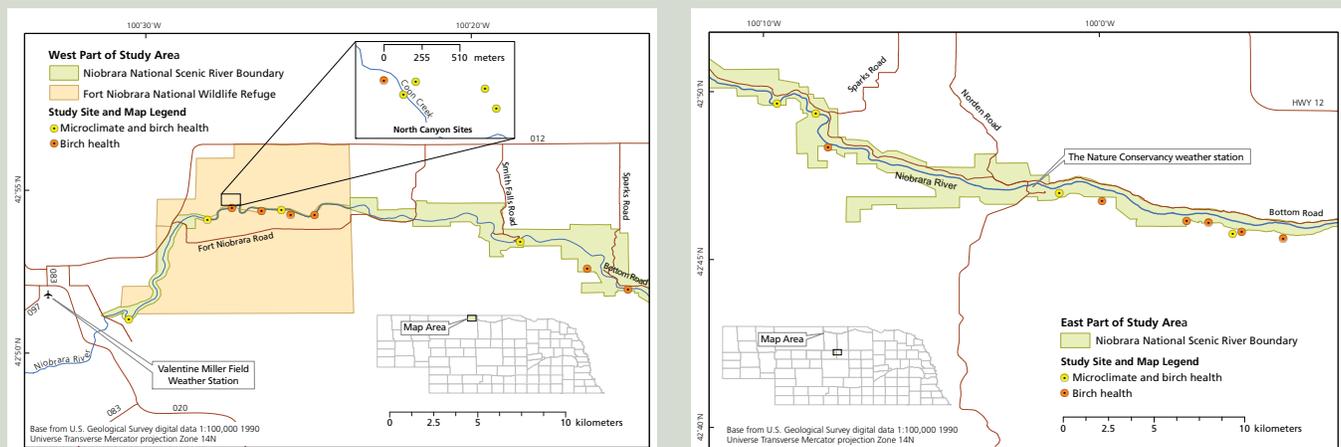


Figure 3. Western (left) and eastern (right) portions of study area showing study site locations. Modified from Stroh and Miller 2009.

Consequently, spring thaw-freeze conditions capable of inducing rootlet injury are likely more frequent in north bank sites; this is probably one reason why birch stands are less common there and why trees there are in worse condition (Stroh and Miller 2009). Meanwhile, spring maximum and minimum temperatures in birch stands on the south side of the river were not significantly different from conditions at Valentine. Thus spring temperatures recorded at Valentine are good predictors of when thaw-freeze conditions might be injurious to trees in these sites.

In summer months, mean daily temperature in all birch sites was about 2°C (3.6°F) cooler than in Valentine. During the study, all birch sites exhibited mean daily temperatures of approximately 22°C (72°F), as opposed to 24°C (75°F) at Valentine. Therefore, summer conditions in all birch sites were close to the 21°C (70°F) average July temperature range limit for birch (USDA 1965). Summer microclimates in these birch stands have likely facilitated the persistence of birch populations in a region otherwise unsuitable for the species and still appear to be close to the temperature limit for birch. Unfortunately, changes in spring weather patterns recorded at Valentine and reflected in birch sites may be causing rootlet injury so that trees die in spite of the still-cool summer microclimates.

Our study looked at weather patterns in a small area and cannot be interpreted as evidence of climate change. However, annual mean temperature in the Great Plains has increased about 0.8°C (1.5°F) compared to the 1960s and 1970s; spring temperatures are projected with 95% likelihood to increase within the next two decades by approximately 0.3 to 2.2°C (0.5 to 3.9°F; USGCRP 2009). Our findings (Stroh and Miller 2009) of significantly warmer March temperatures in the period 1978–2007 as compared to 1948–1977 are consistent with these observations and projections.

### *Increasing frequency of warm spells in March contributes to increased frequency of conditions that can induce rootlet injury in birch trees.*

Although widespread birch dieback is known from other locations, Niobrara River Valley birch populations are isolated and far removed from potential immigrant sources. A large population decline in the context of increased frequency of potentially injurious climatic events will make population recovery more difficult now than in the years 1948–1977, when thaw-freeze conditions were less frequent. These conditions, combined with little evidence of recruitment of young birch and great geographic distance from potential immigrant sources, make future persistence of paper birch populations in the valley uncertain.

Although many trees will likely continue to die or die back, individual trees might improve if living stump sprouts continued to grow. We encountered only a handful of birch saplings in our study (Stroh and Miller 2009); nearly all the mature trees we observed consisted of multiple stems emanating from a common root system, evidence of vegetative reproduction. Smaller subcanopy birch trees die back at lower rates than more exposed canopy trees (Nash and Duda 1951); small trees may be able to survive even if warm spring weather continues to occur for some time. Assisted recruitment activities, such as propagating and planting

birch trees, could help establish young trees that may grow to maturity, maintaining a seed source for future natural recruitment. Persistence via vegetative reproduction is common in relict populations; they can maintain themselves for many generations even with extremely rare recruitment events via sexual reproduction (Eriksson 1996). However, maintaining or reestablishing populations of canopy-sized trees may depend on a reduction in frequency of warm springs observed in recent years.

## Management implications

National parks and other protected areas often encompass regionally unique habitat and therefore frequently harbor relict or disjunct plant populations. Typically, the farther a disjunct or relict population is from its core range, especially if it occupies unusual or unique habitat, the more likely it is to be on a different evolutionary trajectory (Leppig and White 2006). Consequently, relict and disjunct populations are likely to be ecologically and genetically distinct from core populations. Such populations are more susceptible to extirpation because they are usually isolated and small, but are also potentially important for speciation and preservation of evolutionary potential (Lesica and Allendorf 1995). The decline in paper birch populations in the Niobrara River Valley offers resource managers, policymakers, and the public the opportunity to weigh intervention costs against other resource management costs, the risk of failure, and benefits of maintaining species, ecological, and genetic diversity along with the evolutionary potential of species. In the case of the Niobrara Valley birch, loss of this species would eliminate the principal component of the boreal ecosystem represented in the valley, regionally known as the biological crossroads of the Great Plains. Leppig and White (2006) identified approaches to assess conservation value of relict or disjunct populations, including those with local cultural value. Birch populations along the Niobrara Scenic River in Nebraska present an excellent opportunity to incorporate biological and cultural values of relict populations into regional conservation planning efforts.

## Acknowledgments

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## Climate change in Great Basin National Park: Lake sediment and sensor-based studies

By Scott A. Reinemann, Nathan A. Patrick, Gretchen M. Baker, David F. Porinchu, Bryan G. Mark, Jason E. Box

**W**ITH RECOGNITION THAT HIGH-ELEVATION ENVIRONMENTS are highly responsive to changes in temperature and precipitation, it is critical that we improve our understanding of how global climate change will affect freshwater resources and aquatic ecosystems in subalpine and alpine environments (Bradley et al. 2004; Parker et al. 2008). Further, the concern over changing water availability in the Intermountain West adds merit to alpine research. Improving our knowledge of the characteristics and behavior of aquatic ecosystems in alpine environments will strengthen our ability to develop meaningful adaptation strategies and scenarios describing the potential future response of these freshwater systems to projected climate change. Insight will also improve our ability to effectively manage these natural systems and the freshwater resources they contain (Adrian et al. 2009).

Lakes in Great Basin National Park are ideal for studying both past and future changes because of their protected status and relative lack of direct human influence. Paleolimnology is an excellent tool to study past changes by extracting information preserved in lake sediment records. In this way we can study the past distribution of aquatic fauna in high-elevation lakes and establish baseline conditions against which the effects of projected warming in these regions can be evaluated. In addition, paleolimnology can be used to assess how the biotic and abiotic components of aquatic ecosystems have responded to anthropogenic and natural stressors (Fenn et al. 2003; Parker et al. 2008).

Researchers collect a sediment core at Stella Lake in August 2007.

### Abstract

Alpine and subalpine aquatic ecosystems are highly susceptible to direct and indirect effects of climate change, making them ideal study sites. We recovered a sediment core spanning the last 7,000 years from Stella Lake and a core of the last 100 years from Baker Lake in Great Basin National Park, Nevada, in 2005 and 2007. We examined the cores for subfossil chironomid (Insecta: Diptera: Chironomidae; i.e., midge) remains. The midge communities in the lakes underwent little compositional change through much of the 20th century; however, after 1980 a rapid lake-specific faunal turnover was observed. Because of limited dispersal ability and restricted habitats, some lake species will be extirpated by climate change. Fortunately, lake cores show that even during the most arid periods the lakes did not completely desiccate, but continued to support lake biological communities. To complement the limnological work, an air temperature and humidity micrologger network was deployed in 2005 and expanded in subsequent years, now numbering 36 instruments. The sensor network that spans the full park elevation range (1,639–3,892 m/5,377–13,063 ft) indicates coherent seasonal and elevational variations, which help to interpret the paleolimnology data. Climate models indicate increasing temperatures and uncertain change in precipitation for the Great Basin region. Although we may not be able to protect all ecosystems faced with climate change, our collaborative educational research project exemplifies how the National Park Service is equipped to document and interpret climate change.

### Key words

aquatic ecosystems, climate change, paleolimnology, temperature network



**Figure 1.** Lake cores were taken from Baker and Stella lakes, located in and near glacial cirques in Great Basin National Park. The park is situated in east-central Nevada.

We have initiated a collaborative research project to assess climate change in Great Basin National Park, Nevada, using paleolimnology and direct climate observations. Using remains of lake midges (insects in the order Diptera, family Chironomidae) that are preserved in the lake sediments as a proxy for temperature, we have been able to describe variability in the park climate over almost 7,000 years. We also have deployed a network of climate microloggers to complement the limnological work and better characterize current lake-specific climate conditions for comparison with today's midge communities and the longer lake core records.

## Study methods

Using a mini-Glew and modified Livingstone corer, we recovered sediment cores from Stella Lake in August 2005 and Stella and Baker lakes in August 2007 (fig. 1 and photo, previous page). We measured limnological variables, such as surface water temperature, Secchi depth (turbidity), maximum depth, dissolved oxygen, salinity, and specific conductivity at the time of sediment collection using a multimeter probe (Porinchi et al. 2010).

We dated sediments using lead-210 ( $^{210}\text{Pb}$ ) and carbon-14 ( $^{14}\text{C}$ ). We analyzed 12 stratigraphic samples from each lake for  $^{210}\text{Pb}$  content. Six  $^{14}\text{C}$  dates, obtained from wood fragments or conifer needles, indicated that the core spans approximately the last 7,000 years (Reinemann et al. 2009).



Figure 2. Jason Box installs a Lascar air temperature sensor.

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***Using remains of lake midges that are preserved in the lake sediments as a proxy for temperature, we have been able to describe variability in the park climate over almost 7,000 years.***

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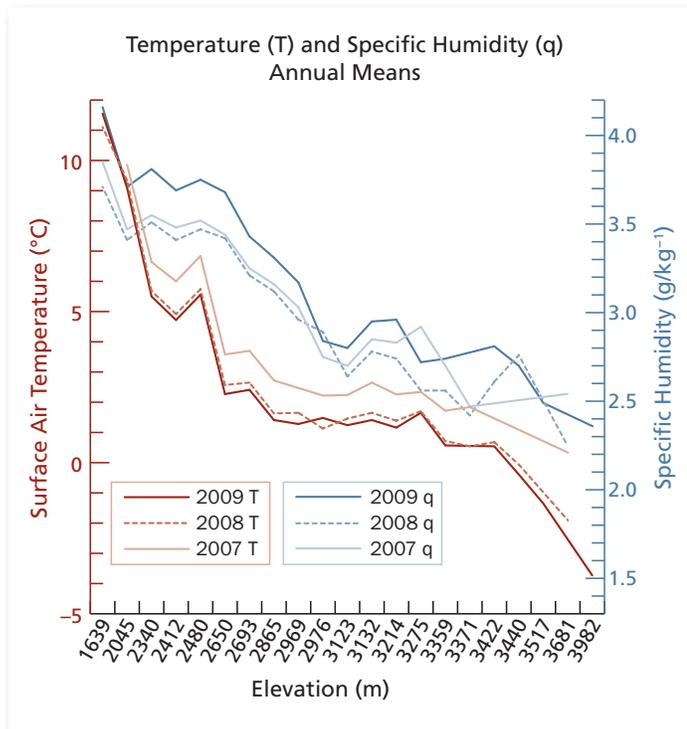
We subsampled the sediment cores in the laboratory for midge analysis. Identifications were based on published keys and an extensive reference collection of midge remains housed at The Ohio State University. The midge-based inference model for average July air temperature was developed for the Intermountain West using a weighted averaging partial least squares approach (Porinchu et al. 2010). The model allows us to create a modern temperature relationship between climate and associated midge communities. Applying this model to past midge communities, we infer average air temperatures during the associated time interval at Stella and Baker lakes.

We installed a micrologger network to record hourly observations of surface air temperature and humidity (fig. 2). The Lascar USB EL-2 sensors situated 1.3–2.0 m (4.3–6.6 ft) aboveground have specified accuracies of  $\pm 0.5^{\circ}\text{C}$  ( $\pm 0.9^{\circ}\text{F}$ ) and  $\pm 3\%$  relative humidity.

## Results

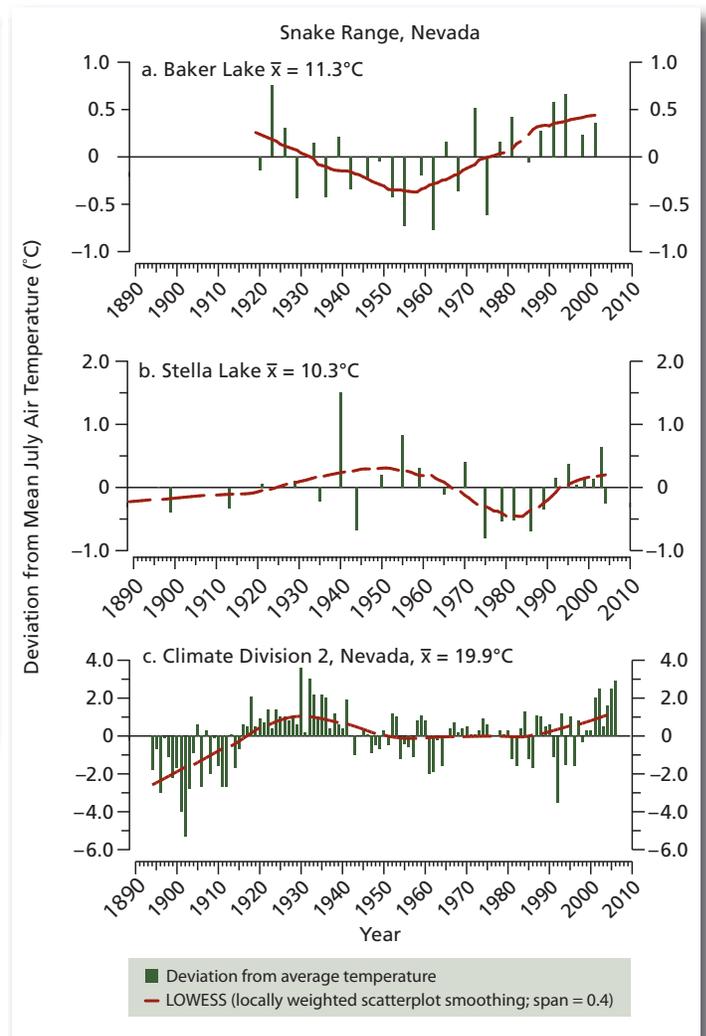
The Lascar sensor network spans the full park elevation range (1,639–3,982 m or 5,377–13,063 ft) and includes sensors located at Baker (3,214 m/10,545 ft), Brown (2,976 m/9,764 ft), Stella (3,123 m/10,247 ft), and Teresa (3,132 m/10,276 ft) lakes. We analyzed data from autumn 2006 to autumn 2010. Data recovery has been limited at the uppermost elevation at Wheeler Peak (3,982 m/13,063 ft) because of vandalism to the sensor. Throughout the park, annual air temperature ranges are extreme, approaching  $50^{\circ}\text{C}$  ( $90^{\circ}\text{F}$ ). The temperature ranges at the lakes were  $40^{\circ}\text{C}$  ( $72^{\circ}\text{F}$ ) or more. We find that temperature and humidity decrease with increasing elevation (fig. 3, next page). The rate of temperature decrease with elevation is commonly taken to be  $6.5^{\circ}\text{C}/\text{km}$  ( $3.57^{\circ}\text{F}/1,000$  ft) (Barry and Chorley 1992). In the park, we observe the lapse rate to vary seasonally from  $4.40^{\circ}\text{C}/\text{km}$  ( $2.41^{\circ}\text{F}/1,000$  ft) in winter to  $7.05^{\circ}\text{C}/\text{km}$  ( $3.87^{\circ}\text{F}/1,000$  ft) in summer. The moisture regime became less linear and more complicated above 3,000 m (9,843 ft).

The midge communities in the lakes experienced compositional change through much of the 20th century; however, the post-1980 lake-specific midge community turnover is notable because of accelerated changes (Porinchu et al. 2010). The recently deposited sediment (last 10 years or so) in Baker Lake is characterized by decreases in relative abundance of three genera, the local extirpation of one genus, and an increase in the proportion of three taxa or organisms. The Stella Lake midge community shifted after 1990 from a community dominated by two genera to a single taxon. A similar degree of change in the Stella Lake midge community occurred approximately 1,000 years ago, during the Medieval Climatic Anomaly (MCA; AD 900–1300).



**Figure 3 (above).** Annual mean values of Lascar-recorded temperature and specific humidity from different elevations in the park in 2007–2009.

**Figure 4 (right).** Midge-based mean July air temperature (MJAT) anomalies in the 20th century for (a) Baker Lake, (b) Stella Lake, and (c) Climate Division 2, Nevada, encompassing averages from several stations in northwestern Nevada (Porinchi et al. 2010).



We reconstructed the 20th-century climate regime for the region using our midge-based inference model (fig. 4). We also used a longer sediment record (with each sample representing about 100 years) to reconstruct the midge-based July temperature record for approximately the last 7,000 years (see Reinemann et al. 2009 and the online version of this article for the full record). Results indicate that the central Great Basin experienced significant temperature shifts over the Holocene Epoch, with peak temperature occurring approximately 5,300 years ago.

## Discussion and conclusions

The recent air temperature and humidity variations at the lakes, as recorded from the Lascar data, suggest that the elevations near and above 3,000 m (9,843 ft) may be particularly susceptible to climate changes, complementing other work (Bradley et al. 2004). Baker, Brown, Stella, and Teresa lakes exist at or above 3,000 m

(9,843 ft). Therefore the Lascar sensors data provide a valuable baseline with which future and past climate conditions at the lake locations may be compared. The July air temperatures we are observing at Stella and Baker lakes are as high as the lake cores have shown over the last 1,000 years and possibly over the last 7,000 years, indicating that climate has recently altered around the lakes of Great Basin National Park.

The findings from the Stella and Baker lake core analysis suggest that the lakes have experienced increasing mean July temperature since 1980 (fig. 3). On longer time scales of climate change ranging from a century to millennia, Stella Lake has experienced large changes in mean July air temperature, corresponding to changes detected in paleoclimate records from around the region. This regional comparison suggests that during times of aridity in the Great Basin, as indicated from pollen and oxygen-18 isotopes from Pyramid Lake, Nevada (Benson et al. 2002; Mensing et al. 2004), Stella Lake experienced elevated air temperatures. Overall,

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*The knowledge that subalpine lakes and their biota have persisted through other warm and dry periods gives staff at Great Basin National Park a positive message to share with visitors.*

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Stella Lake and the park were characterized by a warm and arid middle Holocene followed by a cool and moist neoglacial interval and a return to warmer conditions during the late Holocene. Fortunately, the Stella Lake sediment record reveals that the lake did not completely dry out during past intervals of severe regional aridity (mid-20th century, MCA) and continuously supported a diverse aquatic ecosystem for at least the last 7,000 years (Reinemann et al. 2009; also see the online version of this article at [www.nature.nps.gov/ParkScience](http://www.nature.nps.gov/ParkScience)). These records broaden our knowledge of the temperature conditions that existed during the 20th century and Holocene Epoch in the park by providing an independent quantitative reconstruction of July air temperatures.

The knowledge that subalpine lakes and their biota have persisted through other warm and dry periods gives staff at Great Basin National Park a positive message to share with visitors. As the midge record shows, community structure has changed substantially through time, because of some midge species having relatively narrow temperature ranges. These shifts in the aquatic ecosystem are part of what makes lakes so sensitive and thus so useful as sentinels of climate change (Parker et al. 2008). Park researchers and staff are conducting additional studies and modeling how park resources might respond to climate change. This scientific knowledge will inform managers, which is an important emphasis of the NPS Climate Change Response Strategy. Although we may not be able to protect all ecosystems faced with climate change, this collaborative educational research project exemplifies how the National Park Service is equipped to document and interpret ecosystem change.

## Acknowledgments

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# Long-term change in perennial vegetation along the Colorado River in Grand Canyon National Park (1889–2010)

By Robert H. Webb, Jayne Belnap, Michael L. Scott, and Todd C. Esque

**L**ONG-TERM MONITORING DATA FOR PERENNIAL VEG-  
etation are difficult to obtain (Webb et al. 2009), particularly in remote terrain. Climate change and other anthropogenic influences have impacts on these isolated areas, and managers require scientific evaluations of landscape changes to make informed decisions about whether restoration or mitigation strategies are needed to ensure that resources remain intact for future generations. At the bottom of Grand Canyon (Arizona), the Colorado River winds about 450 km (280 miles) through a narrow, canyon-bound river corridor sustaining desert and riparian vegetation on substrates ranging from bedrock to river sandbars, creating a challenging environment for change-detection monitoring techniques (Belnap et al. 2008).

One method for evaluating change uses ground-based repeat photography to match historical images of landscapes (Webb et al. 2010). This technique, used worldwide to monitor environmental change, has a long history of application in Grand Canyon (Webb 1996). In the early 1990s, a unique set of images of the river corridor was used to document a variety of geomorphic and ecologic changes along the corridor of the Colorado River, including occurrence of debris flows that altered rapids, effects of feral burro grazing, longevity of desert shrubs, and notably influence of warming winter low temperatures on populations of frost-sensitive species (Webb and Bowers 1993; Bowers et al. 1995; Webb 1996). In 2010, 120 years after most of the original photographs were taken and about 20 years after the first series of matches, we revisited our camera stations in Grand Canyon National Park to further document changes in desert and riparian vegetation. Preliminary analysis of 151 new matches shows that original changes documented from 1990 to 1993 appear to be continuing, apparently showing the response of these ecosystems to climate change and river flow regulation.

## Study methods

In 1889 and 1890, river expeditions led by Robert Brewster Stanton documented a proposed railroad route through Grand Canyon using large-format photographs (Webb 1996). A total of 452 images from those expeditions are still in existence. From December 1989 through March 1992, U.S. Geological Survey crews

### Abstract

Long-term monitoring data are difficult to obtain for high-value resource areas, particularly in remote parts of national parks. One long-used method for evaluating change uses ground-based repeat photography to match historical images of landscapes. River expeditions that documented a proposed railroad route through Grand Canyon with large-format photographs occurred in 1889 and 1890. A total of 452 images from those expeditions are still in existence, and these were matched as closely as possible from December 1989 through March 1992. In 2010 and 2011, we are repeating these matches 120 years after the originals and 20 years after the first matches. This repeat photography provides visual information that can be interpreted for changes in terrestrial and riparian ecosystems along the river corridor, including change in the desert plant assemblages related to increasing winter low temperatures and severe drought. The riparian ecosystem, which originally consisted of native species established along the stage of frequent floods, has increased in area, density, and biomass as both nonnative and native species have become established following flow regulation by Glen Canyon Dam. The original and matched images provide the basis for one element of a robust monitoring program for the effects of climate change on ecosystem resources.

### Key words

climate change, Colorado River, dam effects, Grand Canyon, repeat photography, riparian vegetation

obtained high-quality original images and secured matches of all of them with large-format film cameras (Webb 1996). We matched the photographs from as close to the original camera station as possible using standard techniques employed by practitioners of the largest collection of repeat photographs (Boyer et al. 2010). In 2010, we obtained a second set of matches of 151 of the views 120 years after the originals and 20 years after the first matches, using the same techniques and cameras. Although all originals and matches are on film, they are digitized using professional-quality scanners for reproduction and analysis.

This repeat photography provides visual information that is interpreted for changes in terrestrial and riparian ecosystems along the river corridor, both at the camera station and afterward using digital imagery. Plants are identified on-site from the camera sta-

tion within the field of view. For desert species, individual plants can be identified and compared using the geometry of outcrops and rocks in the original and matched images. Mortality and recruitment rates, expressed as percentage of plants per century, are determined through standard techniques (Bowers et al. 1995); for example, recruitment rate is  $R = [N/(N + S)] \times [n/100 \text{ years}] \times 100\%$ , where  $N$  = number of new individuals,  $S$  = number of surviving individuals, and  $n$  = number of years between photographs. For riparian vegetation, the high density of plants in the matched views hinders identification of some individual plants, but general changes in riparian vegetation at the species level can be determined using small areas of views where plants can be discerned. Biomass changes are visually estimated from the matched photographs as increased, about the same, or decreased.

## Findings: Desert vegetation

For desert plant assemblages, repeat photography shows that the framework of the plant community, anchored by long-lived species such as Mormon tea (*Ephedra torreyana* and *E. nevadensis*) and creosotebush (*Larrea tridentata*), is extremely stable (fig. 1). Many species, notably creosotebush, Mormon tea, catclaw (*Acacia greggii*), mesquite (*Prosopis glandulosa*), and blackbrush (*Coleogyne ramosissima*), have individuals that live longer than a century (Webb 1996). Mormon tea and creosotebush individuals live much longer than 120 years and have low rates of mortality. Species-specific mortality rates (percentage of individuals lost per century) were 18% for Mormon tea and 7% for creosotebush (Bowers et al. 1995). Initial results of the second matching effort suggest that, in fact, mortality estimates for these species are high. Recruitment has exceeded mortality, with the net result that desert vegetation assemblages have shown a net increase in individuals. In addition, some species, especially creosotebush, have much larger individuals in the first and second matches (fig. 1), reflecting a general increase in biomass documented in most of the views.

We expected that the early 21st-century drought (Hereford et al. 2006), the most severe in a century, would result in widespread mortality of long-lived species. Our preliminary observations suggest, however, that few individuals of these species died in the two decades between the first and second matches. The ongoing severe drought that began in 2001 could represent future climate, and our preliminary results suggest that mortality of long-lived species will not increase. The effects of this drought, with its decreased winter precipitation, may be offset by normal or above-normal summer precipitation, which can be used by many species that also occur in the Sonoran Desert, or by increased water use efficiency resulting from the increased concentration of carbon dioxide.

Webb and Bowers (1993) and Webb (1996) proposed that a regional decrease in frequency of extreme freezes would lead to an increase in frost-sensitive species along the Colorado River. Barrel cacti (*Ferocactus eastwoodii*), which are common in western Grand Canyon, increased by an average of sixfold between 1890 and the 1990s, a result attributed in part to decreased frost frequency. Increases have continued in the initial matches from 2010 (fig. 1). Brittlebush (*Encelia farinosa*), another frost-sensitive species, increased substantially between 1890 and the 1990s, an expansion also attributable to a rise in low temperatures; our initial observations (fig. 2) suggest that brittlebush continues to expand at our photograph sites, contributing to the overall increase in apparent biomass.

## Findings: Biological soil crusts

Biological soil crusts are communities of cyanobacteria, mosses, and lichens that dominate the soil surfaces of most desert regions (Belnap and Lange 2003), including those at Grand Canyon. These organisms are essential to the soil ecosystem, contributing stability; nutrients, especially nitrogen; and carbon. In Grand Canyon National Park, biological soil crusts at Stanton camera stations are especially well developed (i.e., have a high number of lichens and mosses) on limestone substrates, and moderately well developed on sandstone-derived soils. Soils derived from metamorphic rock have a low cover of lichens and mosses, but are still dominated by cyanobacteria. Crusts with more moss and lichen species contribute greater nutrients and stability than those with fewer species.

Biological soil crusts have low resistance to compression by feet or hooves, but they are extremely resistant to droughts. Repeat photography shows that where these communities are undisturbed by animals or humans, which is the case in most photos, there is almost no detectable change in extent or appearance of biological soil crusts (Webb 1996). In contrast, areas that overlook rapids or favorite visitation spots show a complete, or almost complete, loss of soil crusts to trampling (fig. 3, page 86). Trampling, however, generally left the framework of long-lived species intact, particularly Mormon tea, at least for the short term.

## Findings: Riparian vegetation

Riparian vegetation documented in our repeat photography is sustained by the Colorado River, which has been regulated by Glen Canyon Dam since 1963. Flow regulation has reduced variability in flows, increasing discharge in formerly low-flow seasons and decreasing discharge during the early summer runoff period (Webb 1996). In response to these hydrologic changes,

**Figure 1 (below).** Lava Falls Rapid, mile 179.3, view upstream from river left.



R. B. STANTON, 57-RS-619

A. (27 February 1890). Facing away from the commanding view of Lava Falls Rapid, Robert Brewster Stanton took this upstream-looking photo, showing desert vegetation in the foreground and the river channel in the mid-ground. Creosotebush (*Larrea tridentata*) is the dominant shrub, and five barrel cacti (*Ferocactus eastwoodii*) and one Mormon tea (*Ephedra nevadensis*) are present; this group is typical of the Mojave Desert assemblages of western Grand Canyon. The channel banks are barren below a line of riparian vegetation, likely dominated by mesquite (*Prosopis glandulosa*), that occurred at about the 2,830 m<sup>3</sup>/sec (100,000 ft<sup>3</sup>/sec) flood stage.



R. H. WEBER

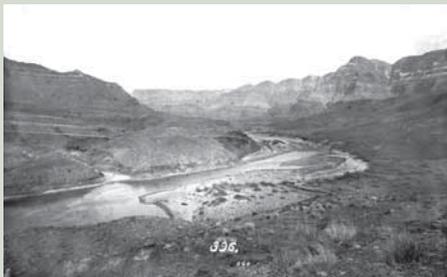
B. (11 February 1990). Most of the creosotebush have persisted in the intervening century since the first photo was taken, as has one individual Mormon tea. While none of the original barrel cacti have survived, the number of individuals has more than tripled to 17, and beavertail pricklypear (*Opuntia basilaris*), Engelmann pricklypear (*Opuntia engelmannii*), and cholla (*Cylindropuntia whipplei*) are now present. We attribute these changes to decreased frequency of severe frost events. Tamarisk (*Tamarix* spp.) and mesquite are prominent along the river corridor.



WILLIAM LEMKE, STAKE 1510C

C. (27 September 2010). Most of the creosotebush have persisted 120 years through this photographic record, which includes other matches made in 1993 and 2003 (not shown). Several barrel cacti present in 1990 have died, probably during the early 21st-century drought, but new replacements increase the number in the view to 22; pricklypear and cholla have also increased in a continuing response to warming winter conditions. Riparian vegetation, leafed out in this image, has increased in the intervening 20 years.

**Figure 2 (below).** View upstream showing Cardenas Marsh, mile 71.3.



R. B. STANTON 57-RS-396

A. (23 January 1890). Stanton took this upstream-looking photo from a hillside below the Cardenas Hilltop Ruin, a prominent archaeological site in the Furnace Flats reach of Grand Canyon National Park. Except for scattered mesquite and what may be clumps of coyote willow (*Salix exigua*), little riparian vegetation is present along the Colorado River. Numerous backwaters occur in this reach, including the prominent complex at right center. The foreground slopes sustain an assemblage of desert vegetation, including Mormon tea (*Ephedra torreyana*), Anderson thornbush (*Lycium andersonii*), and big galleta grass (*Pleuraphis rigida*).



TOM WISE

B. (26 February 1993). The marsh at the mouth of Cardenas Creek (center mid-ground) is nesting habitat for southwestern willow flycatchers, an endangered species. Most of the increased riparian vegetation in the marsh and elsewhere is tamarisk, although Goodding willow (*Salix gooddingii*), coyote willow, arrowweed (*Pluchea sericea*), and other native species have increased as well. The mesquite persistent from 1889 has died back because flow regulation has reduced the size of floods providing necessary water. The backwaters in the view are reduced because of sediment deposition and tamarisk encroachment. In the desert vegetation of the foreground, five individuals of Mormon tea, seven of Anderson thornbush, and three of big galleta grass have survived the 103 years between the original and matched photographs. Brittlebush (*Encelia farinosa*) appears in the view as globose gray-green shrubs and was not present in 1890.



WILLIAM LEMKE, STAKE 1440

C. (20 September 2010). A large open sandbar extends downstream from Cardenas Marsh, but this probably resulted from seasonal deposition of sand from the Little Colorado River upstream and likely will not persist. The Goodding willows in the Cardenas Marsh have crown dieback, suggesting that early 21st-century low-flow conditions may be impacting native species here. Mesquite on the sand dunes behind the marsh appear to be dying or dead as a result of continued flow regulation. Brittlebush is now the dominant shrub on the foreground hillslope, a change we attribute to warming winter conditions. Anderson thornbush continues to persist, but one of the two Mormon teas that persisted until 2003 has died.

**Figure 3.** Crystal Rapid, mile 98.2, view upstream from river right.



**A.** (8 February 1890). When Stanton captured this view looking upstream from what is now known as the right scout point of Crystal Rapid, there was considerable sand among the boulders covered with dense biological soil crust. This high debris fan, probably an Early Holocene relict, was stable with a mature desert vegetation assemblage dominated by Mormon tea and perennial grasses.

**B.** (1 February 1990). A century later, the foreground shows the effects of trampling from river runners visiting the prominent scout point for Crystal Rapid. Most Mormon tea present in 1890 persists, although the biological soil crust and perennial grasses are victims of foot traffic. Catclaw (*Acacia greggii*) and golden-bush (*Isocoma acradenia*) either have become established or are more clearly identifiable. The foreground surface has eroded in response to trampling, as evidenced by additional exposure of rocks. Sandbars in the distance have deflated or at least are less obvious because of the establishment of nonnative tamarisk.

**C.** (22 September 2010). Many Mormon teas survived the intervening 120 years, particularly the one in the right foreground, although perennial grasses that once grew here have not reestablished and biological soil crusts continue to be trampled. Tamarisk, which is leafed out and hence more visible than in 1990, appears to have grown larger.

there has been a substantial change in distribution, abundance, and composition of riparian vegetation in Grand Canyon over the past 120 years. These changes are variable both in space and over time, ranging from imperceptible at some camera stations to striking state transitions at others; for example, some formerly bare channel bars and backwaters have been transformed into densely vegetated riverine marshes (fig. 2, previous page).

Less striking but related changes in riparian vegetation involve the structural simplification and mortality of mesquite and net-leaf hackberry (*Celtis reticulata*). Mesquite once dominated the old high-water zone (occurring at about the 2,830 m<sup>3</sup>/sec flood stage [100,000 ft<sup>3</sup>/sec]) but now occurs mostly well above the new riparian zone (at about the 850 m<sup>3</sup>/sec [30,000 ft<sup>3</sup>/sec] stage), although new individuals have become locally established. Net-leaf hackberry, less common, also is becoming established lower on once-barren channel margins. Whereas nonnative species like camelthorn (*Alhagi maurorum*), Bermuda grass (*Cynodon dactylon*), and tamarisk (*Tamarix ramosissima*, *T. chinensis*, and their hybrids; Friedman et al. 2005) comprise much of the novel assemblages of the new riparian zone, a diverse array of native woody riparian and herbaceous wetland species contribute to the mixture. The more common native species include coyote willow (*Salix exigua*), arrowweed (*Pluchea sericea*), seepwillow (*Baccharis salicifolia*), cattails (*Typha* sp.), common reed (*Phragmites australis*), and sedges. Goodding willow (*Salix gooddingii*) is restricted locally to certain sites.

Transformative changes observed in riparian vegetation in Grand Canyon are attributed to reductions in flood discharges and sediment load by Glen Canyon Dam operations. Reduced flow peaks, depleted of sediment, erode fine-grained bars, deposit coarser sand, and allow vegetation to encroach onto formerly active channel margins. Between 1890 and the 1990s, encroachment of woody riparian vegetation below the old high-water zone—primarily nonnative tamarisk—was expected because of regional trends. From the 1990s to 2010, more native species have become established in this zone. One important hydrologic change is the three short-duration prescribed dam releases with peak discharges of 1,100–1,350 m<sup>3</sup>/sec (40,000–48,000 ft<sup>3</sup>/sec) within the last 16 years (1996, 2004, 2008); these so-called habitat/beach-building floods were released in the winter-spring seasons when viable seeds of some native species, but not nonnative tamarisk, were present.

The spatially rich collection of historical photos from the Stanton expedition, along with precise matches in the early 1990s and 2010, indicate that a more nuanced view of riparian vegetation change along the Colorado River is needed. Encroachment of vegetation over the past two decades onto depositional surfaces that had remained unvegetated until the early 1990s suggests that there are a range of hydrogeomorphic environments that have responded, and may continue to respond, to subtle changes in flow management in the postdam period. Despite relatively large dam releases, in the postdam perspective of flood control, colonization of low-stage habitat continues, creating a much more

diverse riparian assemblage than was present in the 1990s. This is consistent with a growing body of evidence that measurable shifts in riparian vegetation accompany modest climate-related shifts in flow regime for rivers across the Colorado Plateau that are less intensely regulated than the Colorado River (Allred and Schmidt 1999; Birkeland 2002).

## Conclusions

Repeat photography in Grand Canyon documents long-term change caused by a variety of processes, ranging from climate change to visitor impacts and the influence of Glen Canyon Dam. In the zone of desert plants above the direct influence of the Colorado River, a framework of long-lived shrubs and small trees with life spans exceeding a century survived the extreme early 21st-century drought, but is changing with the addition of frost-sensitive species, mostly cacti and brittlebush. The riparian zone continues to respond to changes brought about by operations of Glen Canyon Dam, including flood control, changes in seasonality of large dam releases, and depleted sediment supply. The net result in both desert and riparian ecosystems is an increase in apparent biomass on the landscape. The original and matched images along the Colorado River provide the basis for one element of robust monitoring for the effects of climate change on ecosystem resources in Grand Canyon National Park.

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# The distribution and abundance of a nuisance native alga, *Didymosphenia geminata*, in streams of Glacier National Park: Climate drivers and management implications

By E. William Schweiger, Isabel W. Ashton, Clint C. Muhlfeld, Leslie A. Jones, and Loren L. Bahls

**C**LIMATE CHANGE AND NUISANCE (OR INVASIVE) species pose serious threats to the structure and function of aquatic ecosystems worldwide (Parmesan and Yohe 2003). Over the past 100 years, annual mean air temperatures in Glacier National Park, Montana, have increased twice as much as global temperatures, resulting in declining snowpack, increasing fire frequency, altered hydrology, and loss of the park's iconic glaciers (Pederson et al. 2010; Hall and Fagre 2003). Changes in the hydrological cycle will warm perennial streams, thereby threatening the stability of aquatic ecosystems and potentially increasing the spread of aquatic nuisance species (Rahel and Olden 2008).

*Didymosphenia geminata* (hereafter “didymo”; fig. 1, inset) is a diatom native to mountain habitats of North America and Europe (Blanco and Ector 2009). In recent years didymo has expanded into lower elevations, latitudes, and new regions of the globe (Kumar et al. 2009). In Montana, didymo was first reported in 1929 at Flathead Lake (Prescott and Dillard 1979) and has likely been present in the northern Rockies since at least the end of the last ice age, about 10,000 years ago (Bahls 2007). Didymo can form extensive mats (or blooms), which can be several centimeters thick and up to 20 km (12 mi) in length (Blanco and Ector 2009). Larger blooms can inhibit growth of other algal species, change the composition of aquatic communities, decrease the amount of suitable spawning habitat for fish, and cause changes in stream chemistry (Spaulding and Elwell 2007). Blooms of didymo also greatly decrease the aesthetic appeal of streams—an important

consideration for a tourist destination like Glacier National Park (fig. 1). For these reasons, understanding the causes and consequences of didymo blooms is a high priority for the park, especially for predicting and, where possible, managing its spread.

Because of the lack of data, speculation exists on why there has been a change in distribution of didymo and whether it is linked to climate warming (Bothwell and Spaulding 2008). Recent research suggests that didymo is associated with high mean summer temperature, a stable base flow index (less variation in streamflow), and is more abundant in nutrient-poor systems (Kumar et al. 2009). Here we present NPS monitoring data collected from 2007 to 2009 throughout Glacier National Park to estimate the distribution of didymo and better understand some of the environmental factors associated with its spread in a relatively pristine aquatic system.

## Methods

From 2007 to 2009 we sampled 49 stream sites selected by a spatially balanced probability survey design (Stevens and Olsen 2004) as part of the NPS Vital Signs Monitoring Program (Fancy et al. 2009). In some cases, sites were visited multiple times within and across seasons. At each site, we measured a suite of biological, physical, and chemical variables (Peck et al. 2006). We estimated the abundance of didymo in two ways: First we generated cell counts from composite samples collected from the



INSET: LOREN BAHLS, CURATOR, MONTANA DIATOM COLLECTION

### Abstract

*Didymosphenia geminata* (didymo) is a freshwater alga native to North America, including Glacier National Park, Montana. It has long been considered a cold-water species, but has recently spread to lower latitudes and warmer waters, and increasingly forms large blooms that cover streambeds. We used a comprehensive monitoring data set from the National Park Service (NPS) and USGS models of stream temperatures to explore the drivers of didymo abundance in Glacier National Park. We estimate that approximately 64% of the stream length in the park contains didymo, with around 5% in a bloom state. Results suggest that didymo abundance likely increased over the study period (2007–2009), with blooms becoming more common. Our models suggest that didymo abundance is positively related to summer stream temperatures and negatively related to total nitrogen and the distance downstream from lakes. Regional climate model simulations indicate that stream temperatures in the park will likely continue to increase over the coming decades, which may increase the extent and severity of didymo blooms. As a result, didymo may be a useful indicator of thermal and hydrological modification associated with climate warming, especially in a relatively pristine system like Glacier where proximate human-related disturbances are absent or reduced. Glacier National Park plays an important role as a sentinel for climate change and associated education across the Rocky Mountain region.

### Key words

alga, aquatic nuisance species, climate change, diatom, *Didymosphenia geminata*, Glacier National Park

stream bottom. Second, we visually estimated the thickness and abundance of didymo mats as an index of bloom extent (Kilroy et al. 2005). We defined a “bloom” as a stream reach with a length 40 times its mean wetted width with a Kilroy index greater than 25 (at least 50% of the stream bottom covered by a mat at least 1 cm [0.4 in] thick). A mixed-effects hierarchical model was used to predict stream temperatures throughout the park stream network ( $R^2 = 0.82$ ). We then used associated model outputs to simulate predicted temperatures using the maximum August mean air temperature from our study period (2008: 18.4°C [65.1°F]).

We used a generalized linear model (GLM) employing a log link function and Poisson error term to relate didymo abundance to several predictors, including water chemistry, substrate type, stream temperature, watershed membership, and distance downstream from lakes. Akaike’s Information Criterion was used as a best subsets selection to select the final model(s). We also generated time series models to explore short-term dynamics of didymo abundance using a subset of sites with repeat visits. Finally, by using the properties of the survey design (Stevens and Olsen 2004), we estimated the length of streams across the park that had didymo presence or blooms.

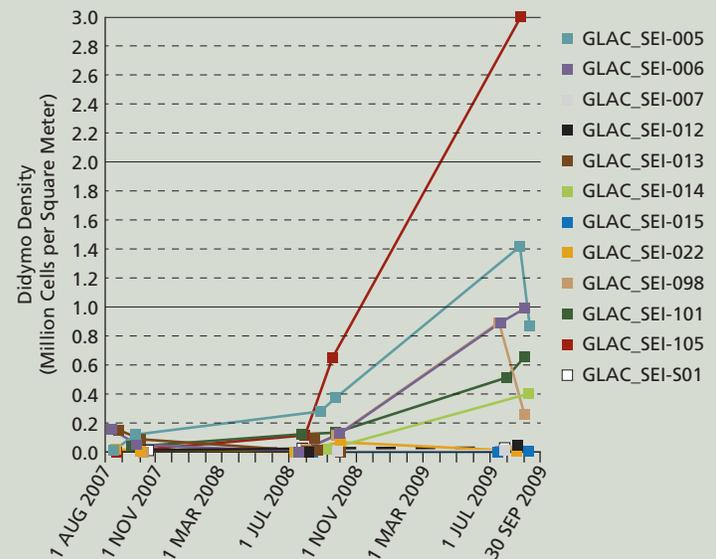


Figure 2. Time series of didymo abundance at 11 sites with repeat visits.

## Results

We estimated that didymo occurred in 64% ( $\pm 17\%$ ) of the flowing water in the park, or about 1,600 km (994 mi) of stream. Furthermore, approximately 5% ( $\pm 3\%$ ) of the stream length in the park was in a bloom state. These results describe, with known confidence and controlled bias, the status of didymo across the complete stream system in the park from 2007 to 2009.

Of the 11 sites revisited in 2007–2009, didymo abundance increased at 8 and decreased at only 1 (fig. 2; the occurrence of blooms increased similarly at the revisited sites—data not shown). Where we had five or more visits, we found statistically significant increases at three sites. Abundance also varied spatially, with the highest abundances of didymo on the west side of the Continental Divide (fig. 3, next page). This suggests great spatial variation in the presence of didymo. Importantly, however, our period of record is short and the sample size of revisited sites is small.

Results from the generalized linear model suggest that didymo abundance was influenced by several environmental factors (e.g., covariates). While all the final model predictors were highly significant ( $p < 0.001$  and  $R^2 = 0.86$ ) and biologically interpretable, we suspect that a meaningful amount of variation in didymo abundance is unexplained and consider the model preliminary. Didymo abundance was positively related to summer water temperatures, the proportion of cobble substrate, and Julian date (indicating that didymo abundance increased during our sample period). Conversely, didymo abundance was negatively related to

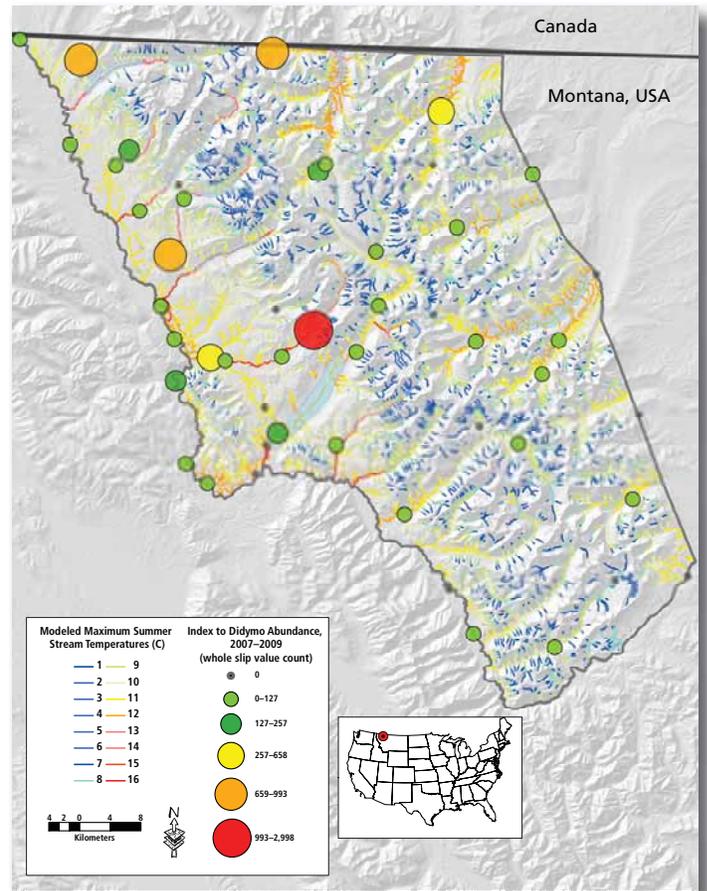
distance from lakes (with higher abundances near lake outlets), total nitrogen concentration, and specific conductance.

Other research has suggested that stable base flows can be a strong predictor of didymo occurrence and abundance (Kumar et al. 2009). We did not measure base flow at all sites in our study. However, the distance downstream from lakes that we did include in our analyses may be a useful proxy, as streamflow is generally more stable near lakes than in further downstream reaches. We suspect that didymo in Glacier National Park responds to the same hydrologic conditions (stable base flow) seen in other studies in similar landscapes (Bothwell and Spaulding 2008). Nevertheless, it is possible that some of the unexplained variance in our models is due to the lack of a detailed hydrologic covariate.

Finally, although we lack detailed data on visitor and angler use at our study sites, we found no associations between human disturbance (e.g., distance to roads or wastewater control structures) and didymo abundance. Didymo is known to be spread by gear used by anglers (Spaulding and Elwell 2007), yet we often found blooms in remote locations that are rarely or never visited.

## Conclusions and management implications

Our results suggest that didymo was widespread and likely became more abundant in Glacier National Park from 2007 to 2009. Although somewhat speculative, our models are generally consistent with other studies of the factors associated with the presence and abundance of didymo (Kumar et al. 2009; Blanco and Ector 2009). Three of the most important and climate change-relevant predictors of elevated didymo abundance we found were higher stream temperature, reduced distance from upstream lakes (as a proxy for stable base flows), and lower nitrogen concentration. If current climate trends continue, each of these may change in ways that favor increased didymo abundance and blooms in Glacier National Park. Stream temperatures are expected to rise (Pederson et al. 2010). Lower summer base flows are more likely given the shift toward earlier runoff and higher contribution from surface flow (Hall and Fagre 2003). Finally, as climate change continues to reduce snowpack, groundwater recharge rates will likely decrease and surface water and rainfall may be larger contributors to base flow, both generally having lower nitrogen concentrations (Hauer et al. 2002). Though we cannot make quantitative predictions given the complexity of the response and the state of our current models, our results do suggest that additional research should be conducted to better understand the dynamics of this species, how it may be influenced by climate change, and how it may impact the aquatic ecosystems of Glacier National Park.



**Figure 3.** Didymo abundance at each of the 49 sites sampled in 2007–2009. Size and color of each point scale with abundance, with larger symbols and redder colors indicating higher abundance. The stream network in the park is displayed using the modeled maximum summer temperatures, with redder colors indicating hotter stream-water temperatures. Lakes are shown in faint blue outline.

Managing native species like didymo presents a complex challenge. National Park Service policy does provide for native species management when a population occurs in an unnaturally high or low concentration as a result of human influences and it is not possible to mitigate the effects of the human influence(s) (Section 4.4.2 in NPS 2006). Although more research is needed in specific locations like Glacier National Park and over longer time periods, the weight of evidence from multiple studies does suggest that didymo is responding to human-caused climate warming and may thus warrant careful management action.

The National Park Service is implementing education and integrated management programs to prevent and reduce the spread of didymo, such as limiting use of felt wading boots and educating visitors about the importance of cleaning fishing gear (see Spaulding and Elwell 2007 for an overview of general recommendations). Nevertheless, given the expected impacts of increased didymo abundance on stream food webs and processes (Kirk-

wood et al. 2007; Bothwell and Spaulding 2008), the species will likely play an important role in the ecology of the park's streams. Our results may be used to help park resource managers implement effective prevention and control measures and as motivation for more detailed research. Conducting research in places like Glacier is important because it allows study of species dynamics in the absence of most direct human stressors. Many drivers of didymo will not be directly controllable by park management. Therefore, perhaps a more important role for the National Park Service is in educating the public about climate change using species like didymo, which, like the emblematic but disappearing glaciers of the park, may be a sentinel of shifting climate regimes.

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# Monitoring direct and indirect climate effects on whitebark pine ecosystems at Crater Lake National Park

By Sean B. Smith, Dennis C. Odion, Daniel A. Sarr, and Kathryn M. Irvine

**W**HITEBARK PINE (*PINUS ALBICAULIS*) GROWS IN tree line habitats throughout the American West, where freezing temperatures, snow, and strong winds can occur any day. Such harsh conditions exclude most other tree species. Tight groups of wind-sculpted and gnarled whitebark pine can form in these extreme sites. These distinct krummholz formations disperse wind and aid in snowpack retention. Subalpine areas occupied by whitebark pine provide inspiring views for national park visitors.

Whitebark pine is threatened by an invasive, nonnative pathogen, white pine blister rust (*Cronartium ribicola*) (MacDonald and Hoff 2001), a fungus that forms lesions, or cankers, of necrotic tissue that girdle tree boles or stems (fig. 1). To complete its life cycle, the fungus must disperse from the pines to an alternative host, a shrub in the genus *Ribes* (currant and gooseberry) or the herbs *Castilleja* (Indian paintbrush) and *Pedicularis* (lousewort) (Geils et al. 2010).

Plump, fleshy, and nutritious whitebark pine seeds are eaten and dispersed by many animals. In particular, Clark's nutcracker (*Nucifraga columbiana*) has developed a mutualistic relationship with the pine (Tomback 2001). This boisterous, robin-sized bird with flashy black-and-white wings and tail has a specialized pouch under its tongue for storing seeds, which it caches widely in the soil. Seeds that are not eaten by the nutcracker maintain populations of the pine. McKinney et al. (2009) found that nutcrackers decrease in whitebark stands as tree mortality increases.

In a study of historical data from sites in and around Crater Lake National Park, Daly et al. (2009) noted significant increases in average and winter temperatures, but no change in precipitation over the last 100 years. The implications of recent climate change for the whitebark pine ecosystem are complex and likely to operate through direct and indirect mechanisms. The most significant, observable effect of climate change is indirect: warmer temperatures in recent years have allowed mountain pine beetles (*Dendroctonus ponderosae*) to shift upward and persist in higher-elevation forests (Logan et al. 2010). Murray (2010) reported that mountain pine beetle is now the primary cause of whitebark pine mortality at Crater Lake, presently at a rate of 1% annually from all causes. Other indirect, pathogen-related effects could occur

## Abstract

Whitebark pine (*Pinus albicaulis*) is the distinctive, often stunted, and picturesque tree line species in the American West. As a result of climate change, mountain pine beetles (*Dendroctonus ponderosae*) have moved up in elevation, adding to nonnative blister rust (*Cronartium ribicola*) disease as a major cause of mortality in whitebark pine. At Crater Lake National Park, Oregon, whitebark pine is declining at the rate of 1% per year. The Klamath Network, National Park Service, has elected to monitor whitebark pine and associated high-elevation vegetation. This program is designed to sample whitebark pine throughout the park to look for geographic patterns in its exposure to and mortality from disease and beetles. First-year monitoring has uncovered interesting patterns in blister rust distribution. Incidence of rust disease was higher on the west side of the park, where conditions are wetter and more humid than on the east side. However, correlating climate alone with rust disease is not straightforward. On the east side of the park, the odds of blister rust infection were much greater in plots having *Ribes* spp., shrubs that act as the alternate host for a portion of the rust's life cycle. However, on the park's west side, there was not a statistically significant increase in blister rust in plots with *Ribes*. This suggests that different species of *Ribes* associated with whitebark pine can increase pine exposure to blister rust disease. There is also convincing evidence of an association between total tree density and the incidence of blister rust. Warmer temperatures and possibly increased precipitation will affect both whitebark pine and *Ribes* physiology as well as tree density and mountain pine beetle numbers, all of which may interact with blister rust to cause future changes in tree line communities at Crater Lake. The Klamath Network monitoring program plans to document and study these ongoing changes.

## Key words

blister rust, climate change, Crater Lake National Park, disease susceptibility monitoring, mountain pine beetle, whitebark pine

if climate increasingly favors blister rust. For example, the rust favors moister conditions, and increased precipitation in winter is an expected trend under climate change in the Pacific Northwest. Conversely, summers may be drier and inhibit the formation and spread of rust spores and fruiting body development. Daly et al. (2009) noted an increasing tendency for the summer dry season to extend into early fall at Crater Lake and elsewhere in the Oregon Cascades over the last few decades. Direct effects of longer, high-elevation growing seasons because of climate change could



**Figure 1.** Whitebark pine with an active blister rust infection (canker).

favor the pines, as many high-elevation trees are growing more rapidly today (Bunn et al. 2005). However, direct effects of longer growing seasons could increase competition among pines and other trees that can grow faster than the notoriously slow-growing whitebark pines. This could act as an indirect effect that places the pine at a competitive disadvantage, especially if whitebark pine populations cannot migrate quickly enough to competition-free environments like those in which they presently live.

Whitebark pine and its associated community of species are among the vegetation resources identified for long-term, focused monitoring by the Klamath Inventory and Monitoring Network of the National Park Service. This monitoring is designed to complement park monitoring of whitebark pines at Crater Lake National Park (Murray 2010). The network's monitoring is also specifically designed to help identify factors related to whitebark pine infection and mortality from disease and beetles, and to track changes in all high-elevation vegetation structure, function, and composition related to climate and other factors. By tracking disease progression and beetle impacts, as well as vegetation change, we can link observed changes to direct and indirect climate-mediated mechanisms and determine the effects of climate change and other factors on whitebark pine. The network has completed its first year of monitoring, sampling 20 plots at Crater Lake National Park. We briefly highlight our initial findings here.

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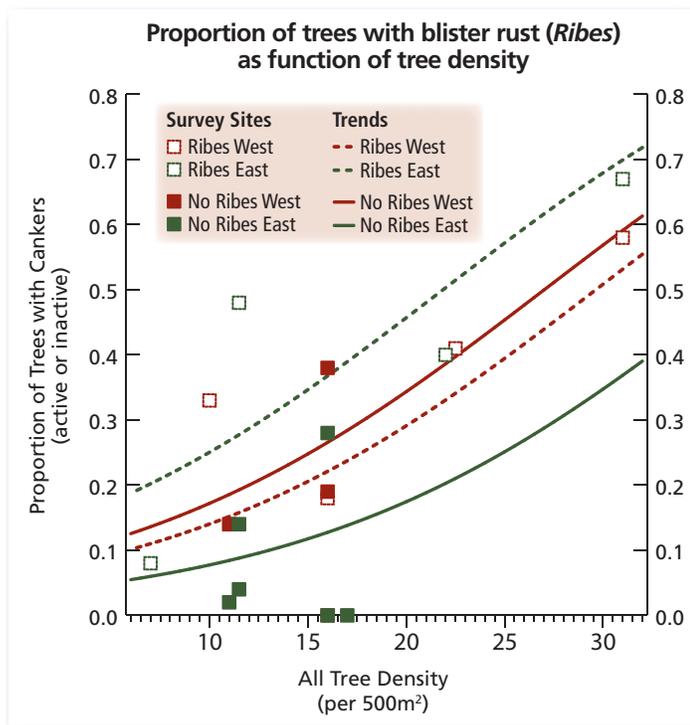
*Whitebark pines are more exposed to rust spores if they are associated with Ribes that are more susceptible to blister rust. . . . The roles of tree density, alternative hosts, and geography will need to be sorted out through focused research and continued monitoring.*

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## Key findings

The leading cause of whitebark pine mortality was indirectly related to climate change: mountain pine beetle. Beetles caused 21% of tree deaths, followed by mortality from blister rust (20%), a pattern consistent with findings of Murray (2010). However, 54% of trees had an indeterminable cause of death. We also found that active infections were more common on the west (11%) than on the east side of the park (4%) ( $P = 0.04$ ). There was convincing evidence of a positive association between tree density and the probability of a tree having evidence of a blister rust infection (logistic regression,  $P < 0.01$ ; fig. 2, next page). One hypothesis explaining this finding is that increased competition for resources where tree density is highest may make whitebark pines more susceptible to blister rust. This would suggest that if longer growing seasons under future climate continue to cause increased tree growth and density at higher elevations, blister rust may be favored.

There was also evidence suggesting that the east-to-west geographic pattern is mediated, in part, by the alternative hosts, *Ribes* species. Plots with *Ribes* on the east side of the park had a higher incidence of blister rust than those without *Ribes*, but this was not the case on the west side (fig. 2). We can only speculate on explanations for this finding. For example, species of *Ribes* differ in their susceptibility to blister rust infection (Maloy 1997). Whitebark pines are more exposed to rust spores if they are associated



**Figure 2.** As tree density increases by one tree per 500 m<sup>2</sup> (598 yd<sup>2</sup>), the odds of blister rust infection increase by a factor of 1.09 (95% confidence interval: 1.02–1.17). Although the rate of change is the same for plots with or without *Ribes* located on the west or east side of Crater Lake National Park, sites with *Ribes* on the east side tend to have the highest proportion of infected trees.

with *Ribes* that are more susceptible to blister rust, as *Ribes* with high susceptibility are more likely to become infected and transmit spores. Additional research may provide insight into the roles of individual *Ribes* species and possible interactions with climate.

These initial findings suggest that climate change sets in play a complex array of direct, indirect, and potentially confounding changes in whitebark pine ecosystems. The roles of tree density, alternative hosts, and geography will need to be sorted out through focused research and continued monitoring, but it is already clear that increased mountain pine beetle activity associated with warming temperatures is adding to the loss of an estimated one-third of whitebark pine since the arrival of blister rust in the 1930s. Multifaceted monitoring by the Klamath Network and by Crater Lake National Park will allow the National Park Service to track future change in the pines, pathogens, and composition of the associated vegetation community. It will also help the Service to identify genetically resistant trees for use in propagation programs, to aid the park's future whitebark pine restoration efforts (Murray 2010). In addition, we plan to implement whitebark pine monitoring at Lassen Volcanic National Park in California.

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### Pika research

The research team conducted systematic pika occupancy surveys in 2010 and again in summer 2011. These surveys occur across a range of latitudes, longitudes, elevations, and substrate types (talus slopes vs. lava beds), from which researchers will develop both park-specific and regionally appropriate habitat models for assessing pika vulnerability to climate change. Analyses of fecal DNA collected during occupancy surveys will document recent gene flow patterns. Distribution, habitat, connectivity, and genetic data and models will be combined to conduct a quantitative vulnerability assessment that explicitly predicts pika response to climate change.

In 2010, the team evaluated pika site occupancy and habitat at 677 randomly located sampling sites in eight national park units following the peer-reviewed protocol developed in the Upper Columbia Basin Network (Jeffress et al. 2011; see page 18). Occupancy of sites was determined by surveying for pikas, pika calls, fresh food caches or “hay piles,” and fresh fecal pellets in plots with a 12 m (39 ft) radius. We also collected 387 fecal samples at the five parks where genetic work is funded. Additional surveys at new and existing sites occurred in summer 2011, though the final tally of completed surveys for the year was not available as the article went to press. Analyses of occupancy results and fecal samples are ongoing and final reporting is planned for 2012.

The large geographic area of this project provides a range of local- and regional-scale information, enabling meaningful analysis of key drivers of pika distribution under a shifting climate regime. Because of the habitat requirements and limited dispersal ability of American pikas, we expect that habitat in national parks will be of increasing importance as refugia and

therefore as source populations for future colonization. Anticipated products from this project include distribution maps and databases to support long-term pika management in each park, habitat connectivity models based on gene flow among selected pika populations, and climate change vulnerability assessments for pikas across the Intermountain and Pacific West regions.

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more information, see Jeffress et al. 2011 and the Web site of the Upper Columbia Basin Network at <http://science.nature.nps.gov/im/units/ucbn/monitor/pika/pika.cfm>.

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