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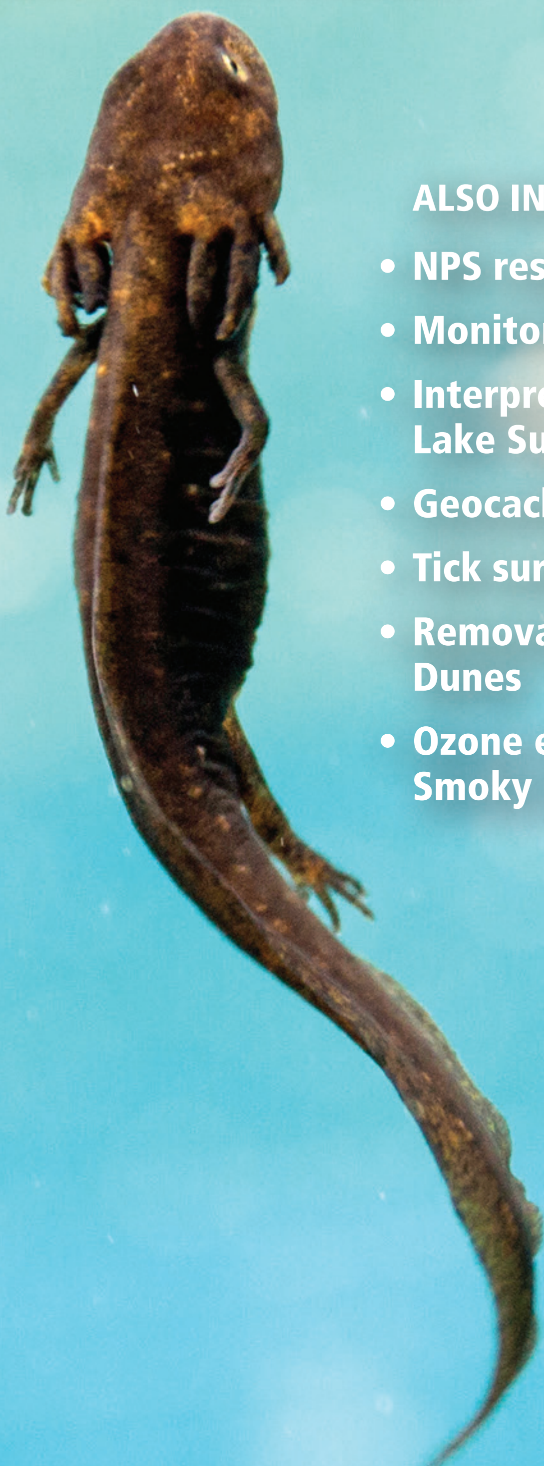
Integrating Research and Resource Management in the National Parks

National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science
Office of Education and Outreach

THE MAZAMA NEWT: CLASH WITH NONNATIVE CRAYFISH IN CRATER LAKE



ALSO IN THIS ISSUE

- NPS response to climate change in wilderness
- Monitoring physiological stress in pikas
- Interpretive primer: The Midcontinent Rift and Lake Superior parks
- Geocaches as interpretation at Everglades
- Tick surveillance along the Appalachian Trail
- Removal of artesian wells from Great Sand Dunes
- Ozone effects on ecosystem services at Great Smoky Mountains

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Editorial office
Jeff Selleck
National Park Service
NRSS/OEO
P.O. Box 25287
Denver, CO 80225-0287

E-mail: jeff_selleck@nps.gov
Phone: 303-969-2147
Fax: 303-987-6704

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Park Science is a research and resource management journal 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 in summer or winter. The publication serves a broad audience of national park and protected area managers and scientists and provides for 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 presented in nontechnical language. The editor and board or subject-matter experts review content for clarity, completeness, usefulness, scientific and technical soundness, and relevance to NPS policy.

From the Editor

A theme for the ages

The articles that follow illuminate many of the virtues of science: adaptability, repeatability, scalability, affinity for scrutiny and compounding, and ultimately its ability to produce knowledge. In this snapshot of seemingly unrelated studies, science is the theme, the common thread, and it is a strong bond.

Our cover article reviews what is known about an endemic species of salamander in Crater Lake and its troubling competition with an invasive, nonnative species of crayfish. The researchers couple this knowledge with an experiment of their own to better understand interactions between the species, and like sunlight penetrating the lake, science spotlights the problem and indicates the need for a management response.

Elsewhere social science provides a much-needed feedback loop for managers of designated wilderness areas with regard to wilderness stewardship as our climate changes. The report is a variation on a familiar theme: whether or not to act in wilderness and the implications of an active or passive stewardship approach for the preservation of wilderness character.

Researchers also investigate the abundance and distribution of pathogen-carrying ticks along the Appalachian Trail. The study reveals the importance of providing information for hikers to take preventive measures to help ensure their health and safety as they enjoy the trail.

Physical and intellectual interaction with parks is a prime opportunity awaiting visitors to the areas we manage, and the research about geocaches in Everglades gives us a useful perspective on this. Geocaching combines finding one's way to park features and preplaced interpretive information by way of a GPS device and a list of coordinates. As the researchers report, the activity can stimulate learning, provide physical challenge, and be designed to minimize resource damage. This information may help increase confidence in managers to create similar programs in other parks.

This collection of articles is not easily summed up in a thematic word or phrase. It is a fascinating array of field-based studies and findings that illustrate the flexibility, usefulness, and robust nature of science as our fundamental way of knowing.

—Jeff Selleck, Editor

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

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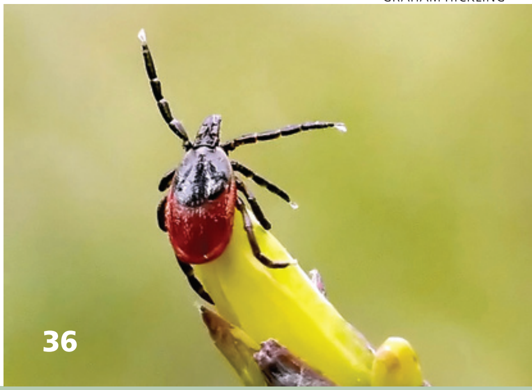

ON THE COVER

A Mazama newt swims toward the surface of Crater Lake, Oregon. This endemic species' liquid habitat is as clear and clean as nearly any on Earth, yet it faces increasing competition from a nonnative predator.

GABRIELLE DIAMOND

COLORADO STATE UNIVERSITY AND USGS/SARAH J. GARZA

NPS/TAMARA BLETT

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Fall 2015
Seasonal issue. November release.
In production

Winter 2015–2016
Seasonal issue. February release.
Contributor's deadline: 15 October

Spring 2016
Seasonal issue. June release.
Contributor's deadline: 15 February

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Research Summary

Crater Lake National Park seasonal biological technician Steve Metzger returns Mazama newts to Crater Lake after studying behavioral interactions between newts and signal crayfish in mesocosms.

The impact of introduced crayfish on a unique population of salamander in Crater Lake, Oregon

By M. W. Buktenica, S. F. Girdner, A. M. Ray, D. K. Hering, and J. Umek

CRATER LAKE IS THE DEEPEST LAKE IN THE UNITED States, with a maximum depth of 592 m (1,943 ft), and is well-known for its blue color and extreme water clarity (Bacon et al. 2002; Larson et al. 2007). Nearly a half million visitors annually come to enjoy the stunning beauty of this special lake, which formed roughly 7,700 years ago in the collapsed caldera of Mount Mazama, a volcano in the southern Oregon Cascade Mountains (Bacon et al. 2002). The lake has been protected in Crater Lake National Park and managed in near-pristine condition since 1902, yet this remarkable ecosystem is not immune to the impacts of introduced species. A unique population of salamanders in Crater Lake is now threatened by introduced crayfish, and park managers face the challenge of controlling crayfish to conserve the native amphibian.

The Mazama newt (*Taricha granulosa mazamae*) is a distinct population of the more widely distributed rough-skinned newt (*T. granulosa*) and occurs only within Crater Lake. The Mazama newt was first formally described in the 1940s and proposed as a subspecies characterized by unusually dark ventral pigmentation (Myers 1942; Farner and Kezer 1953; fig. 1, page 7). Recent genetic analyses of rough-skinned newts by the University of Idaho and the U.S. Geological Survey (USGS) confirmed that newts in Crater Lake are genetically distinct from other Pacific Northwest newt populations (University of Idaho and the Orianne Society, S. Spear, conservation geneticist, personal communication, Moscow, Idaho, 31 December 2014). In addition, the Mazama newt differs from rough-skinned newts outside of Crater Lake in appearance, toxicity, and possibly life history expression.

The rough-skinned newt is the only terrestrial animal to contain tetrodotoxin (TTX), the same neurotoxin that is found in deadly saltwater puffer fish (Tetraodontidae) and blue-ringed octopus (*Hapalochlaena* spp.) Most rough-skinned newts outside the Crater Lake caldera contain measurable levels of TTX and are highly toxic (Brodie 1968). Rough-skinned newts have evolved bright coloring to warn predators that they are poisonous. In addition to their darker ventral coloration (fig. 1), Mazama newts have extremely low toxicity levels (average whole newt toxicity = 0.50 µg TTX) compared with newt populations sampled at other high-elevation sites outside the caldera (6.91 µg TTX) and newts at low-elevation sites along the Oregon coast (2,000 µg TTX; Stokes et al. *in press*). Our recent observations also suggest that the Mazama newt has a more predominantly aquatic life history than typical rough-skinned newts, although terrestrial Mazama newts were reported to be common historically "under the rocks and driftwood along the shore" of Crater Lake (Farner and Kezer 1953).

Newts in Crater Lake may be less toxic and darker in color than other populations for multiple reasons. Lower toxicity may be associated with the absence or reduction of a terrestrial life history stage and terrestrial predation, the lack of evolutionary history with native aquatic predators, or insufficient energy available to produce toxins in the ultra-oligotrophic (i.e., nutrient-poor) lake environment. Darkened coloration on ventral surfaces may also represent a darkening response to elevated ultraviolet radiation (Belden and Blaustein 2002; Garcia et al. 2009), which penetrates to great depth in the exceptionally clear lake (Hargreaves et al. 2007).

By analyzing scanned newt images, we have quantified color differences between Mazama newts and rough-skinned newts from nearby populations. Our analysis used average gray scale intensity of the images, ranging from 0, representing true black, to 255, representing complete white. Using this approach we were able to summarize the color distribution for representative samples of newts captured inside and outside of Crater Lake and express this variation in gray scale values. Preliminary results suggest that the ventral surfaces of Mazama newts are quantitatively darker. For example, in figure 1, the newt from Crater Lake (mean gray scale intensity = 39) contains more black color than the newt from nearby Spruce Lake (mean gray scale intensity = 91).

Abstract

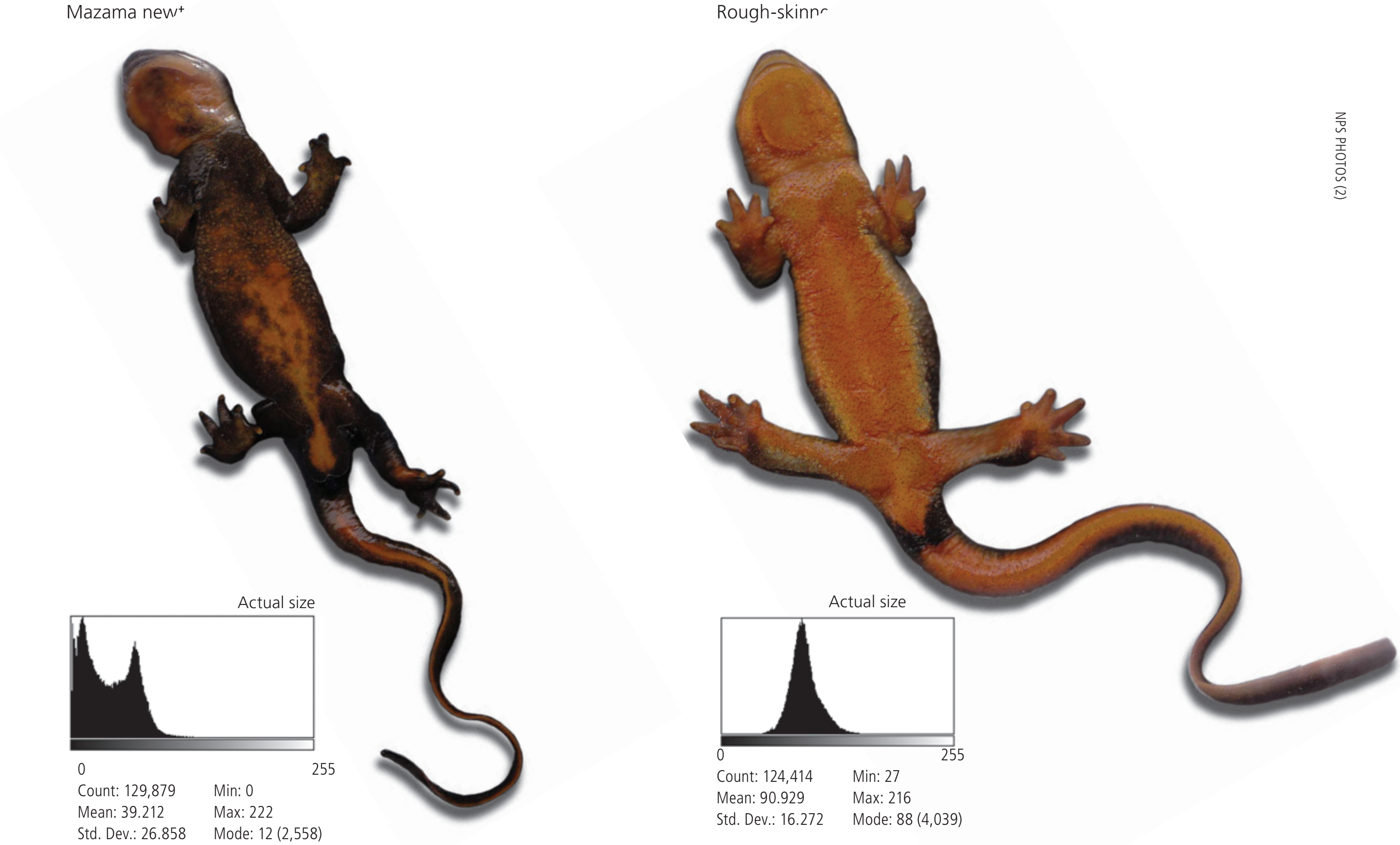
The signal crayfish (*Pacifastacus leniusculus*) was introduced to Crater Lake in 1915 and is now displacing a native salamander. Before the introduction of this crayfish species, no crayfish existed in the lake. A proposed subspecies of the rough-skinned newt (*Taricha granulosa*), the Mazama newt (*T. granulosa mazamae*) is reportedly endemic to Crater Lake, Oregon. The Mazama newt is morphologically, genetically, and physiologically distinct from populations of newts outside of the lake. Observations by park biologists through the 1900s suggested a decline in Mazama newt distribution and an increase in signal crayfish abundance, which led us to investigate current distribution, relative abundance, and interactions between crayfish and newts. Results indicate that crayfish have expanded in distribution to occupy nearly 80% of the lakeshore. Newts remain in areas that crayfish have yet to invade but are almost entirely absent in areas occupied by crayfish. Isotopic signatures of carbon and nitrogen in newt and crayfish tissue indicate that the two species eat similar food items and occupy a similar position (primarily predacious) in the food web. Abundance of other aquatic invertebrates was dramatically reduced in locations with crayfish compared with areas of the lake without crayfish. Mesocosm experiments conducted with newts and crayfish revealed that crayfish prey on newts, displace newts from cover, and generally alter newt behavior when the two species co-occur. This evidence, taken together, suggests that further crayfish expansion likely will cause additional declines in newt abundance and distribution, and could lead to extinction of the unique Mazama newt. Conserving this irreplaceable component of Crater Lake's native fauna will be a challenge for park resource managers.

Key words

Crater Lake, invasive species, rough-skinned newt (*Taricha granulosa*), signal crayfish (*Pacifastacus leniusculus*)

The degree of genetic, morphological, and physiological differentiation in the Mazama newt is particularly striking given the close proximity of more typical rough-skinned newt breeding populations within 12 km (7 mi) of Crater Lake. These traits suggest that newts residing within the steep-walled caldera have been physically isolated from outside newt populations and have adapted to the local lake environment.

Prior to the introduction of nonnative fish in 1888 and the subsequent introduction of crayfish, the Mazama newt presumably occupied a key ecological niche for thousands of years as the top aquatic predator in Crater Lake. Through the mid-20th century, park naturalists described newts as common along the shoreline, including Wizard Island (Farner and Kezer 1953). As recently as the 1980s, newts were frequently observed at Wizard Island and near the boat dock facility on the north shore of the lake.



NPS PHOTOS (2)

Figure 1. Examples of ventral (underside) coloration and gray scale analysis of a Mazama newt from Crater Lake and a rough-skinned newt from nearby Spruce Lake, Oregon. Assessments of newt coloration were completed using only the ventral surface from head to vent (i.e., cloaca) and excluding legs and tail (see Beukema 2011). The resulting histogram from this region displays a darkness value from 0 (black) to 255 (white) on the x-axis; the y-axis represents the number of pixels in the image of each shade along the gray scale. Using this approach we were able to summarize the intensity distribution for each individual's ventral surface expressed in gray scale values.

Signal crayfish (*Pacifastacus leniusculus*) were introduced into Crater Lake as food for nonnative trout and salmon in 1915. Crayfish significantly and fundamentally modify shoreline aquatic plant and animal communities because of their aggressive behavior and consumption of a wide variety of plants and animals, including invertebrates, small fish, vascular plants, algae, and detritus (Momot 1995; Light 2003; Lodge and Hill 1994; Stenroth and Nyström 2003; Geiger et al. 2005).

Investigating crayfish impacts on newts and invertebrates

Prompted in part by the apparent decline in Mazama newt distribution at Crater Lake, we conducted several studies to investigate the effect of crayfish on newts and benthic aquatic invertebrates such as insects, snails, and worms that live on the lake bottom and are typical food sources for newts (Farner 1947). Our current

> *The degree of genetic, morphological, and physiological differentiation in the Mazama newt . . . suggest[s] that newts residing within the steep-walled caldera have been physically isolated from outside newt populations and have adapted to the local lake environment.*

studies describe the distribution and relative abundance of newts and crayfish, stable isotopic signatures of carbon and nitrogen for newts and crayfish, densities and relative abundance of invertebrates in areas of crayfish presence and absence, and the behavior of newts and crayfish in mesocosms (enclosed experiments in a pseudo-natural environment designed to control key variables).

In the century following their introduction, crayfish have colonized a large portion of the lake and may be expanding further in distribution and abundance. We documented spatial distribution and relative abundance of both crayfish and newts along the shoreline beginning in 2008 using snorkel surveys and baited traps at regularly spaced intervals around the lakeshore (fig. 2). We also documented vertical depth distribution of crayfish at five locations around the lake using baited traps set at 18 discrete depths ranging from 1 m to 300 m (3–984 ft) (fig. 3). Snorkel surveys indicated that crayfish occupied 47% of the 31 km (19 mi) of rocky shoreline in 2008 and nearly 80% in 2013 (fig. 4). In addition, we captured crayfish in traps to 250 m (820 ft) below the surface of the lake (fig. 3). Newts were locally abundant in areas where crayfish were not observed but rarely occurred in sites where crayfish were present (fig. 2). Notably, newts were consistently absent from Wizard Island and the north shore of the lake where they had been distributed historically (Farner and Kezer 1953).

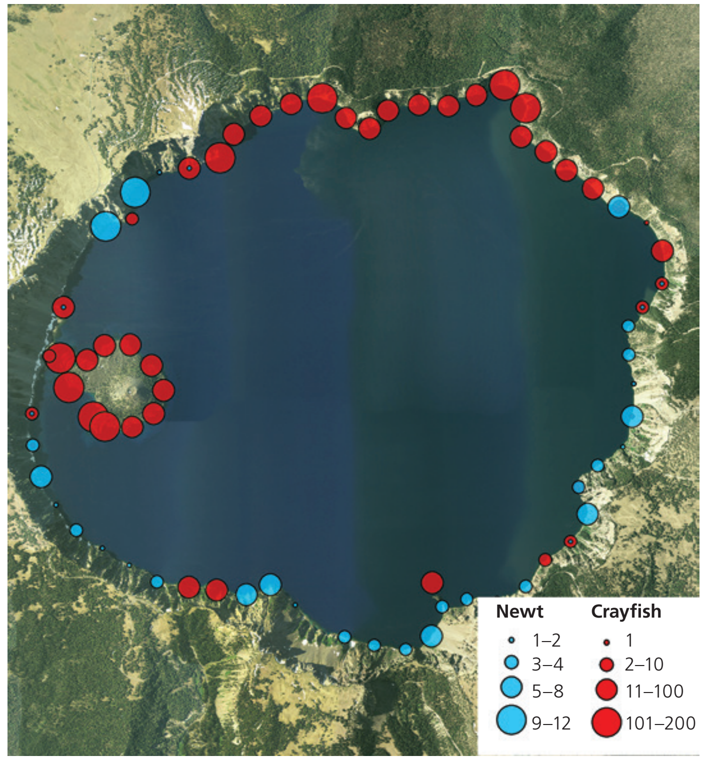


Figure 2. Spatial distribution and relative abundance of signal crayfish (red) and Mazama newts (blue) in 2012, Crater Lake, Oregon. Introduced crayfish are widespread along as much as 80% of the shoreline and appear to be excluding newts.

Evaluation of the stable isotope composition of carbon and nitrogen in plant and animal tissue is often used to understand animal diets and the potential for food web interactions in aquatic ecosystems (Fry 1991). The composition of these isotopes in the tissues of an organism is a direct reflection of the sources of energy the organism consumes. Carbon isotopes reflect the source of primary production (e.g., phytoplankton vs. vascular plants). Similar carbon isotopic signatures between organisms in the same ecosystem indicate a dependency or use of similar sources of carbon and, consequently, similar diets. Nitrogen isotopes indicate trophic level position in the food web, that is, primary producer (e.g., algae and plants), primary consumer or "grazer" (e.g., organisms that eat algae or plants), secondary consumer (e.g., zooplankton and many aquatic insects), or predator (e.g., fish, newts, and crayfish). Similar nitrogen isotopic signatures indicate similar positions in a food web. The average isotopic signatures of crayfish (muscle tissue) and newts (average of muscle, liver, and tail tissues) in Crater Lake (expressed as the ratios of heavy to light isotopes in the samples compared with accepted standard ratios) were $\delta^{13}C$ (‰) crayfish −8.11 ± 1.33 (mean ± standard deviation), newt −9.64 ± 2.16; and $\delta^{15}N$ (‰) crayfish 5.20 ± 0.51, newt

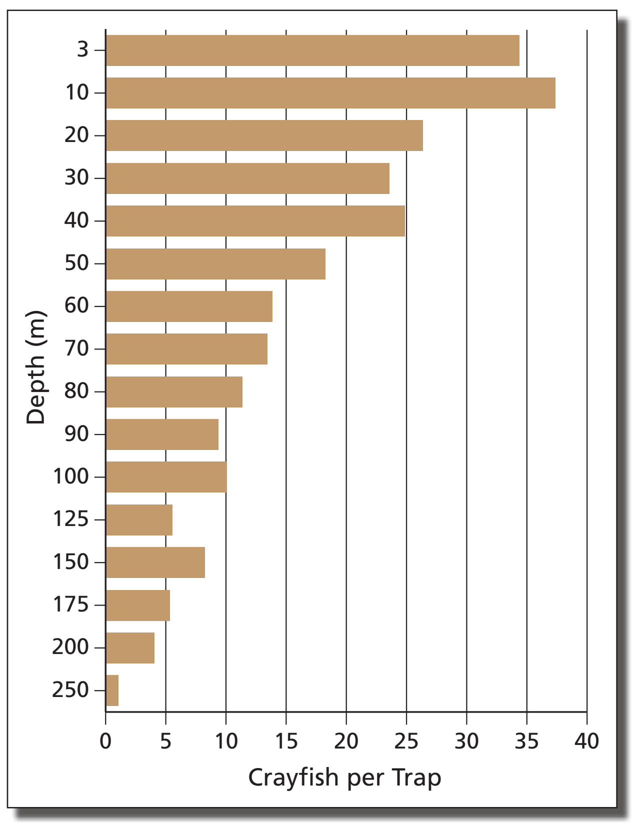


Figure 3 (right). Average September depth distribution of signal crayfish at Cleetwood Cove, Crater Lake, Oregon, 2008–2014.

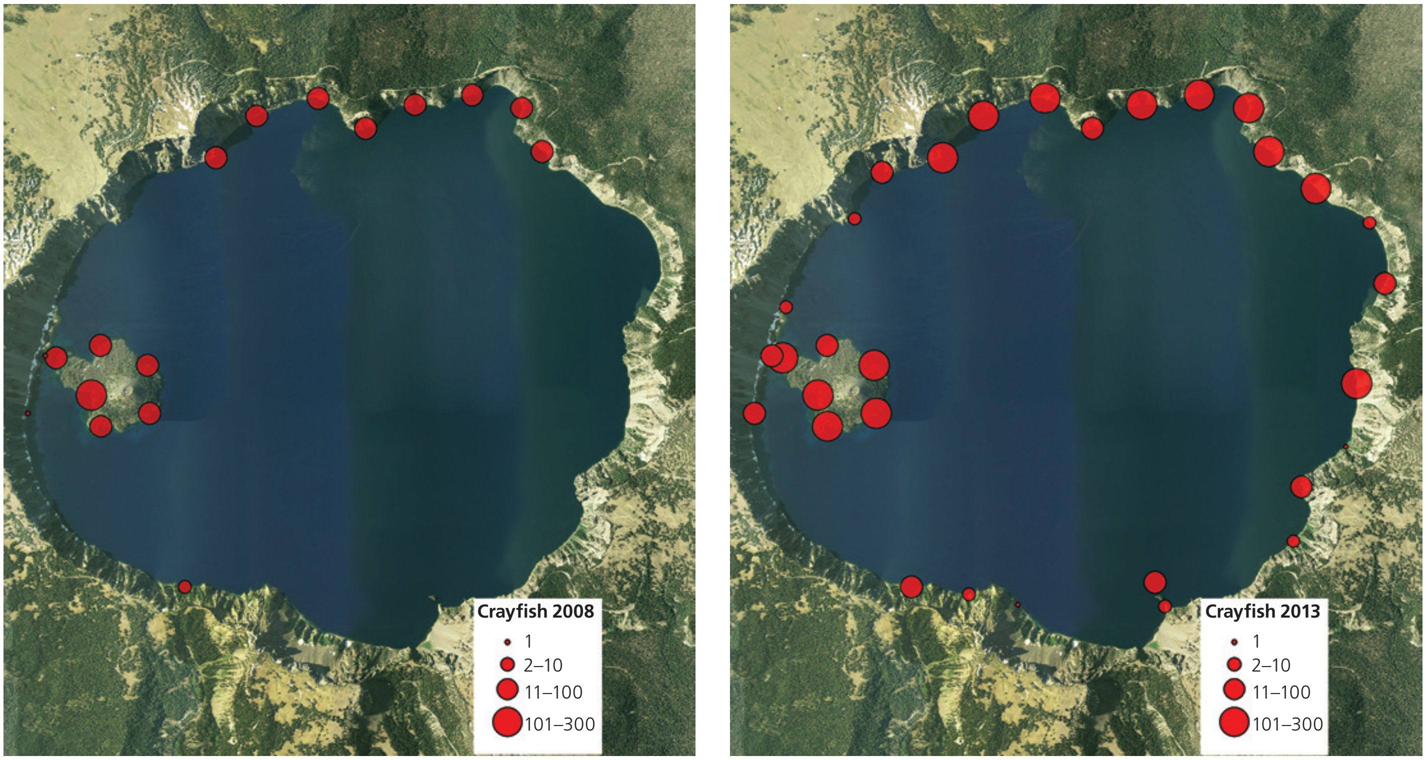


Figure 4. Spatial distribution of signal crayfish in Crater Lake, Oregon, 2008 and 2013. Data were collected similarly in the two years by time-constrained snorkel surveys.

5.46 ± 0.66. These values are remarkably similar between species, indicating that crayfish and newts in Crater Lake eat similar food items and occupy the same trophic level (primarily predators).

We sampled benthic aquatic invertebrates in areas of the lake with and without crayfish. Scuba divers collected samples from hard substrate at depths of 1, 3, and 10 m (3, 10, and 33 ft) using a battery-powered vacuum. After collection, invertebrate samples were preserved in ethanol and later sorted and identified to the lowest taxonomic resolution possible—genus for all taxonomic groups except oligochaete worms (identified to family) and midges (identified to species). Invertebrate abundance was dramatically reduced in locations with crayfish compared with areas of the lake without crayfish (Henery et al. 2012). For example, the average density of aquatic worms was 93% lower in crayfish areas than in areas not occupied by crayfish. Likewise, midge density was 84% lower in crayfish areas. On average, the total density of invertebrates was reduced by 78% in areas with crayfish. Given the substantial overlap in diet between crayfish and newts, such dramatic reductions in food availability in an already unproductive lake ecosystem may have profound negative effects on newt growth and survival.

We conducted mesocosm experiments at Wizard Island to evaluate newt behavior in the absence and presence of crayfish at multiple densities. The experiments used 380-liter (100 gal) tanks to simulate the rocky shoreline conditions of the lake (fig. 5, next page). The bottoms of the tanks were covered with gravel, and one large protruding rock was located in the middle of each tank for cover. We circulated lake water through the tanks to replicate ambient water quality conditions. One newt was placed in each of the eight tanks and allowed 60 minutes to acclimate. Trials started with the addition of crayfish (zero, two, four, or eight crayfish per tank) and lasted 60 minutes, during which time newt and crayfish behavior were documented every 2 minutes. The highest crayfish density in the mesocosms (eight crayfish) was 17.6/m^2 (1.6/ft^2). Crayfish density in areas of the lake with high abundance ranged from 13 to 24/m^2 (1.2 to 2.2/ft^2). Behavior was quantified into four categories: swimming, resting on the bottom, occupying rock shelter, and actively avoiding crayfish. Fifteen 60-minute trials (each with eight mesocosms) were completed. We conducted experiments during daylight and after dark with both adult and larval newts to investigate whether behavioral patterns and responses to crayfish differed between life stages or under different lighting conditions or times of day. The day and night experiments were also initiated because in Crater Lake, newts are

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Figure 5. Experimental mesocosms used to evaluate Mazama newt and signal crayfish behavior on Wizard Island, Crater Lake, Oregon. A team of NPS scientists observed the interaction between newts and crayfish in tanks designed to mimic natural habitat.

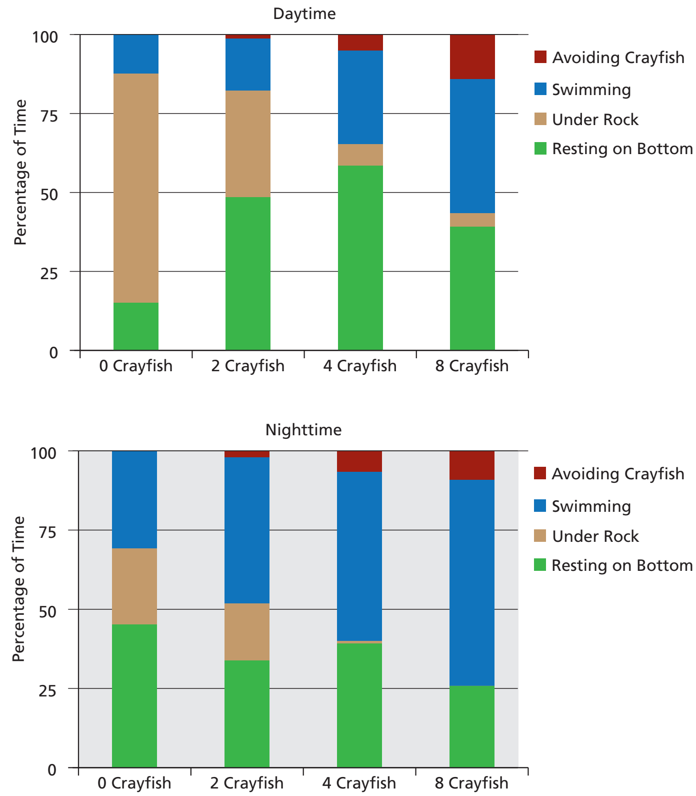

Figure 6. Day (top) and night (bottom) adult Mazama newt behavior in the presence of zero, two, four, and eight signal crayfish, from mesocosm experiments on Wizard Island, Crater Lake, Oregon, 2012–2013.

generally observed under cover during the day and in the open at night, presumably foraging on the rocky bottom.

The mesocosm experiments showed that crayfish displaced newts from under rocks and also caused the newts to spend more time swimming (fig. 6). Newts in tanks with crayfish spent more than 200% more time in the open than did newts in tanks without crayfish. As the density of crayfish increased, newts spent progressively more time swimming. Following encounters with crayfish, newts in the tanks almost always swam to the water surface to breathe air. As the density of crayfish increased, the number of trips to the surface also increased. In the most crayfish-dense treatments at night, adult newts were swimming to the water surface more than once per minute on average during the 60-minute trials. By contrast, newts in crayfish-free control tanks rarely surfaced. Such a large increase in time spent swimming presumably increases newts' energy expenditure, which may be particularly detrimental in such an extremely low-nutrient lake. Displacement into the open during the day and swimming to the water surface following a crayfish encounter leave newts prone to predation from introduced fish as well as increased exposure to ultraviolet-B radiation (UV-B). Ultraviolet radiation is harmful to many species of amphibians, including rough-skinned newts, and is thought to decrease newt growth and increase activity level (Blaustein et al. 2000). Impacts of UV-B may be especially severe in Crater Lake, where high elevation is combined with extremely transparent water, resulting in unusually high UV-B penetration deep into the lake (Hargreaves et al. 2007).

We also observed direct predation on newts by crayfish during mesocosm trials. In the 76 experimental replicates with crayfish present, 10 newts were captured by crayfish, killed, and usually eaten immediately. Nine of the 10 newts killed were larvae, even though tanks with larvae represented only 42% of the total number of experimental trials. Larvae may not recognize crayfish as a potential predator or they may be less able than adults to escape crayfish attacks. At night larvae spent more time resting on the bottom of the tank than adults (68% compared with 33% of the time) even when crayfish were present. There were occasions during the experiments when larval newts shared the area under the rock cover with crayfish, usually to the detriment of the larvae. Another possible direct effect of crayfish that we have not investigated is predation on newt eggs, which are laid under rocks and large debris along the shoreline.

Although Mazama newts are also vulnerable to predation by non-native trout, our research and annual surveys suggest introduced crayfish have played a dominant role in the newt population's decline. The risk of trout predation is present throughout the lake and along the entire shoreline, yet newts have persisted in areas without crayfish while disappearing from crayfish-occupied sites. Mazama newts are occasionally found in the stomachs of rainbow trout (*Oncorhynchus mykiss*) in Crater Lake but make up a very small proportion of the trout diet (Brode 1938; Buktenica et al. 2007). The behavioral interactions observed in mesocosms indicate that crayfish presence may increase exposure of newts to fish predators. Thus, two introduced species, rainbow trout and signal crayfish, likely have additive or synergistic negative effects on native newts.

Conclusions and management challenges

The native Mazama newt is morphologically, genetically, and physiologically distinct from populations of rough-skinned newts outside of Crater Lake. Based on multiple lines of evidence, we believe that introduced crayfish are expanding in distribution and displacing Mazama newts. The mechanisms of displacement identified here include direct predation by crayfish, newt avoidance of crayfish-occupied habitats, and competition for food. Indirect effects may include increased energy expenditure by newts during avoidance and surfacing behavior, increased exposure to ultraviolet radiation, and increased predation of newts by introduced fish as newts are supplanted from their preferred habitats during the day. Further expansion of signal crayfish in Crater Lake will lead to additional declines in Mazama newt abundance and distribution and perhaps to extinction of the proposed newt subspecies.

Park managers now face the difficult challenge of slowing or stopping the spread of crayfish to preserve the Mazama newt. The National Park Service is mandated to protect and preserve natural resources in parks, particularly taxa such as the Mazama newt that are rare, endemic, or unique to specific parks. In other, smaller lakes, crayfish removal or suppression has been used with varying success to reduce negative ecological effects of nonnative crayfish. Suppression strategies include mechanical (e.g., trapping), physical (e.g., habitat manipulation, draining), biological (e.g., use of predators), biocidal, and autocidal (e.g., X-ray irradiation) approaches (Gherardi et al. 2011). Hein et al. (2007) demonstrated that sustained trapping over five years combined with fish harvest restrictions resulted in a 95% reduction in rusty crayfish (*Orconectes rusticus*) from a 64-hectare (158 acre) lake in Wisconsin. Unfortunately, trapping alone is not always successful, in part because this approach is biased toward larger individuals. Recently, X-rays have been tested to sterilize male crayfish in a laboratory with the aim of developing the technology for invasive crayfish control (Aquiloni et al. 2009). Also, sex pheromones have been employed to increase crayfish trapping efficiency (Aquiloni and Gherardi 2010).

In a very large and deep water body such as Crater Lake, where crayfish have been found hundreds of meters deep, it is unclear whether any current approach will be feasible for reducing the distribution of crayfish. Park staff conducted crayfish control experiments at Phantom Ship, a small island on the southeastern side of the lake that has a relatively low density of crayfish. Continuous trapping during the summer months of 2012, 2013, and 2014 resulted in 1,840, 2,087, and 1,629 crayfish removed during the three successive years, without any apparent reduction in crayfish density. The number of crayfish observed during standardized snorkel surveys at Phantom Ship actually increased over this same period, from 30 in 2011 (before crayfish removal) to 177 in 2014. It was evident from this pilot removal study that any meaningful crayfish control efforts will require significantly more resources than are currently available at Crater Lake National Park. Crater Lake managers may need to focus attention on the current edges of crayfish distribution and attempt merely to slow further expansion, assuming that large crayfish-free areas still remain.

A workshop is proposed to bring together scientists and resource managers who have direct experience confronting and managing crayfish invasions. The workshop will draw upon the expertise of participants to determine objectives, management options, and a conceptual model of the expected outcome of alternative actions to control crayfish or otherwise conserve Mazama newts. Because introduced crayfish are an increasing threat to aquatic resources globally (Gherardi et al. 2011), recent work to assess the effect of crayfish on newts and benthic invertebrates in Crater Lake, together with results of any future suppression efforts, may have far-reaching implications both within the National Park System and for aquatic resource management more generally.

Acknowledgments

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(IACUC) protocol 2011-40 and NPS investigator permits CRLA 2010-SCI-0013 and CRLA 2011-SCI-0011. Toxicology was conducted in collaboration with Dr. Amber Stokes and Dr. Edmund Brodie, Jr., Utah State University (USU), and in accordance with USU's IACUC protocol 1008. Stable isotope analyses were conducted by the laboratory of Dr. John Roden, Southern Oregon University, and invertebrate taxonomy was performed by the UNR Aquatic Ecosystems Analysis Laboratory.

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About the authors

***M. W. Buktenica**, **S. F. Girdner**, and **D. K. Hering** are with Crater Lake National Park, Oregon. **A. M. Ray** is with the NPS Greater Yellowstone Network, Bozeman, Montana. **J. Umek** is with the Aquatic Ecosystems Analysis Laboratory, Department of Biology, University of Nevada, Reno. Please direct correspondence to mark_buktenica@nps.gov.*

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Feature

The National Park Service response to climate change in wilderness

By Katie Nelson

Abstract

Wilderness advocates debate whether climate change warrants an active or passive approach to wilderness stewardship. Surveying the 49 units of the National Park System that administered designated wilderness in 2012 and early 2013, this baseline study describes the active approach to wilderness stewardship in a climate change context. The response rate was 94%. A majority of the responding parks report taking action in wilderness in response to climate change. Respondents also reported that these activities affected wilderness character. This response will be welcomed by some and worrisome to others. Nevertheless, the lens of wilderness character continues to provide appropriate and necessary complexity to evaluate stewardship responses.

Key words

climate change, prohibited uses, wilderness character

With the nation celebrating the 50th anniversary of the Wilderness Act in 2014, we have had an opportunity to reflect on how wilderness stewardship is evolving in response to today's challenges. By drawing artificial boundaries across the landscape, the act was intended to preserve federal lands from impacts wrought by unrestrained use and management. Yet boundaries do not protect these lands from the pervasive effects of climate change. To preserve wilderness character and address a dilemma unforeseen by the act's visionaries, wilderness managers must grapple with a number of potential responses. For example, in the wake of climate change, Joshua Tree National Park is predicted to lose many of its Joshua trees (Cole et al. 2011). The following list expresses hypothetical scenarios for what wilderness managers might consider in this context (adapted from Cole and Yung 2012):

- Wilderness managers could allow the use of drip irrigation to maintain the namesake species in its current range. But should they?
- What about introducing Joshua trees to other areas of the wilderness that are expected to harbor more favorable habitat in the future?
- Or perhaps they could introduce other "neo-native" species to areas left in the wake of dying Joshua trees?
- Should park officials refrain from such interventions and instead allow "nature" to take its course—accepting whatever evolves as a novel ecosystem?
- Would pursuing management restraint justify increased monitoring to document and learn from Joshua tree retreat?
- What if this monitoring compromises other wilderness qualities?

These are the kinds of questions facing wilderness managers in parks across the nation. Impacts of climate change vary with the diversity of the nation's parks. It may be sea-level rise along the coasts, melting glaciers, insect outbreaks, migrating species, decreasing snowpacks, altered fire regimes, or changing visitor-use seasons. At base, climate change begs the question, "How should we respond?" Even in the midst of this change, the Wilderness Act (1964) requires wilderness character to be preserved using only the minimum actions and tools to the extent necessary.

Section 4(c) of the Wilderness Act prohibits certain uses such as motorized equipment, mechanical transport, and construction of permanent structures and installations, among others. Prohibited uses may be employed in certain circumstances, e.g., if the use is deemed "necessary to meet minimum requirements for the administration of the area" for the purpose of wilderness.

National Park Service (NPS) policy requires parks to complete a Minimum Requirements Analysis (MRA) prior to undertaking wilderness management activities. MRAs help managers and scientists employ a thoughtfully targeted approach to preserving wilderness character. They document the determination of whether a proposed action involving a prohibited use or an action that could potentially affect wilderness character is necessary to meet the minimum requirements for the administration of the area for the purpose of wilderness. When environmental assessments or environmental impact statements are prepared for projects in wilderness, an MRA should be included as part of the document.

The interagency Arthur C. Carhart National Wilderness Training Center has developed resources to help wilderness managers prepare MRAs. The NPS Stewardship Division provides guidance on how to effectively carry out that responsibility.

Although the Wilderness Act requires wilderness character to be preserved, it neglects to define this concept. Keeping It Wild, an interagency strategy to monitor wilderness character, has defined five qualities of wilderness character: untrammeled, undeveloped, natural, solitude or primitive and unconfined recreation, and other features of value (Landres et al. 2008). These qualities have been lifted directly from the definition of wilderness as stated in the act. They are commonly considered in MRAs and in wilderness character monitoring.

Despite such guidance, there remains a lively academic debate over whether climate change warrants an active or hands-off approach to wilderness stewardship. Should wilderness managers and scientists exercise a responsibility to do everything they can to monitor and adapt to climate change in these most protected places? (See, e.g., Frelich and Reich 2009.) Or should they instead exercise humility through restraint and learn from unmanipulated benchmarks while avoiding unintended consequences (as described by Landres 2010)? The debate tends to be framed as a trade-off between two qualities of wilderness character: natural and untrammeled (Cole 2001). The hands-off approach is said to benefit the untrammeled quality as the active approach benefits the natural quality. However, this trade-off ignores the other qualities of wilderness character, which also figure into wilderness management planning.

Because there is no nationwide database to document wilderness stewardship activities and their effects upon wilderness character, the current debate highlights individual case studies and hypothetical scenarios. However, this study provides the first glimpse at wilderness stewardship on the national scale by describing responses to climate change in NPS-administered wilderness. As a result, this study gives those discussing appropriate stewardship approaches the fabric within which to sew their arguments.

The hands-off approach is said to benefit the untrammeled quality as the active approach benefits the natural quality.

Methods

This study is focused on designated wilderness administered by the National Park Service in its national parks, monuments, lakeshores, and seashores (hereafter referred to as "parks"). To develop a list of potential survey respondents, I requested that NPS superintendents overseeing these parks choose a park representative who could participate in this study. This representative was to be someone who could best speak to the park's climate change and wilderness issues. All superintendents complied. Respondents were informed that their responses could be associated with their park in publications; however, their name and contact information would remain confidential.

I sent a pilot survey to a sample of these individuals and solicited their feedback. Based on this feedback, I developed an online survey using both open-ended and closed-form questions. Closed-form questions asked respondents about the level and type of ongoing stewardship activities occurring in designated wilderness and in response to climate change. Respondents indicated the topics being addressed by these projects. I use the term *project* to describe a stewardship activity happening in wilderness that may consist of several different actions or components coordinated to achieve a set of objectives. The project may be external or NPS-led. The term is intended to capture the number of decision points that have been made to approve climate change adaptation activities in wilderness. *Monitoring projects* identified in this study have been driven by the intention to observe and track climate change and its effects within wilderness boundaries. *Management projects* intervene to modify or guide the effects of climate change in wilderness.

Respondents also provided information about specific *management actions* taken on the ground. Management actions are the more discrete components of a management project. Examples include prescribed burning, using pesticides, and thinning vegetation. I generated a layer of detail about the impact of management actions by asking whether uses constrained by the Wilderness Act had been approved in the process. I refer to these constrained uses (motorized vehicles and equipment, roads, commercial enterprise, mechanical transport, and structures and installations) as *prohibited uses*—reflecting language included in the Wilderness Act. Monitoring and management projects and management actions are referred to collectively as *stewardship activities*.

After exporting survey results into a data analysis program, SPSS, I coded qualitative data according to common themes using content analysis. I then analyzed these findings alongside quantitative responses. Through this process, several overarching themes emerged that I classified into consistent concepts. I incorporated the strongest of these themes and concepts, as well as notable outliers, in the discussion below.

Results

With a response rate of 94%, participants described stewardship responses to climate change in wilderness and how these activities affect wilderness character. Respondents had spent an average of 9.4 years working in their park. They had also accumulated an average of 11.4 years of experience working in wilderness stewardship. Respondents held a variety of positions. Many were chiefs of resource management or chief rangers. Biologists and geologists also responded. Some superintendents filled out the survey themselves. About one-half (48%) of the 46 respondents indicated that they served as the wilderness coordinator for their park. Their different backgrounds, training, and areas of expertise may have affected how questions were interpreted and how participants responded.

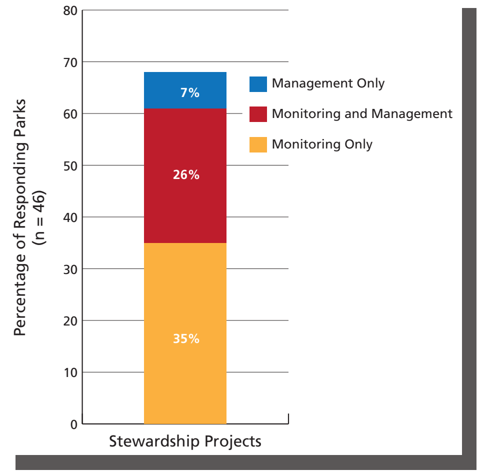
Stewardship activities

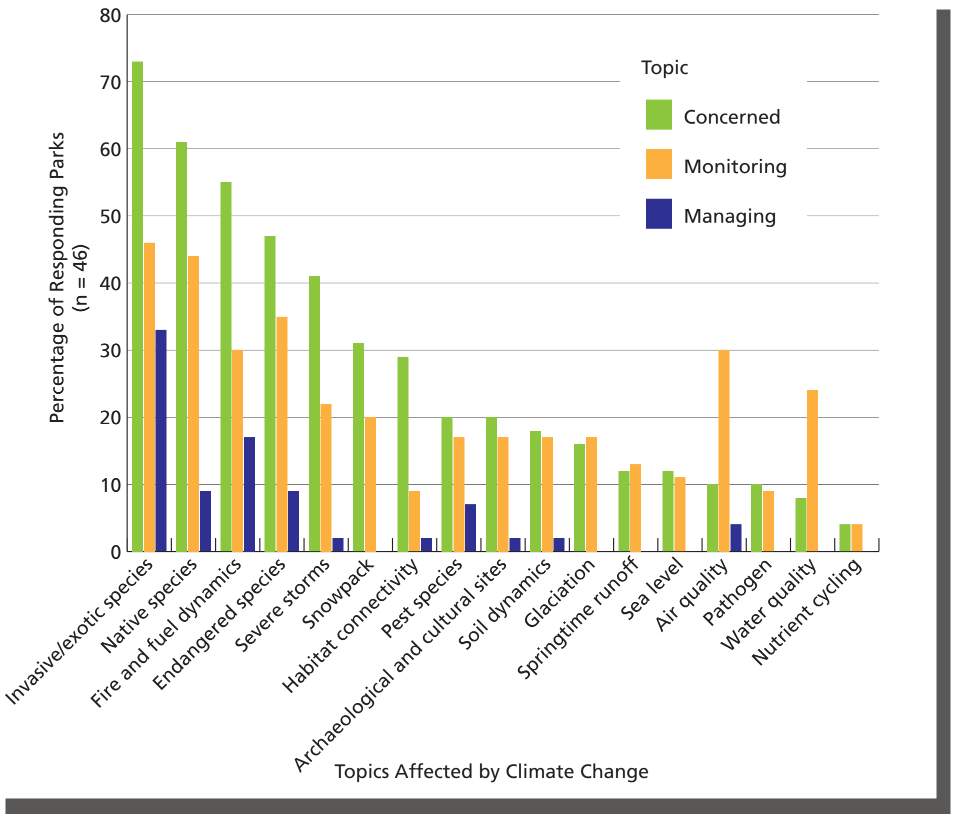
Climate change prompted ongoing wilderness stewardship activities in more than two-thirds of responding parks (fig. 1). Response to climate change in NPS-administered wilderness amounted to 120 monitoring projects and 27 management projects.

The responses described here likely underestimate the overall stewardship response to climate change in NPS-administered wilderness. Several respondents commented that additional stewardship activities went unreported in the survey because these activities, though related to climate change, had not specifically been designed to address its effects. Other respondents noted that their park was just beginning to consider the effects that climate change would have in their wildernesses.

Figure 1 (right). Percentage of parks carrying out monitoring and management projects to address climate change and its effects in National Park Service–administered wilderness (n = 46 park units).

Figure 2 (below). Percentage of parks concerned about, monitoring, or managing listed topics in National Park Service–administered wilderness for the purpose of addressing climate change and its effects (n = 46 park units).





Exotic species, native species, endangered species, and fire were the topics most commonly addressed in park wilderness with respect to climate change (fig. 2). "Exotic and invasive species" was the most commonly monitored and managed topic as well as the most commonly ranked concern.

Respondents reported information about specific management actions addressing climate change in wilderness (figs. 3 and 4, next page). Most of those actions were associated with fire (suppressing or prescribing it) or removal of undesired species.

Despite constraints stated in the Wilderness Act, prohibited uses were approved for 60% of management actions responding to climate change in NPS wilderness (fig. 3). Although actions associated with exotic and invasive species were common, these actions were also among the least likely to have employed a prohibited

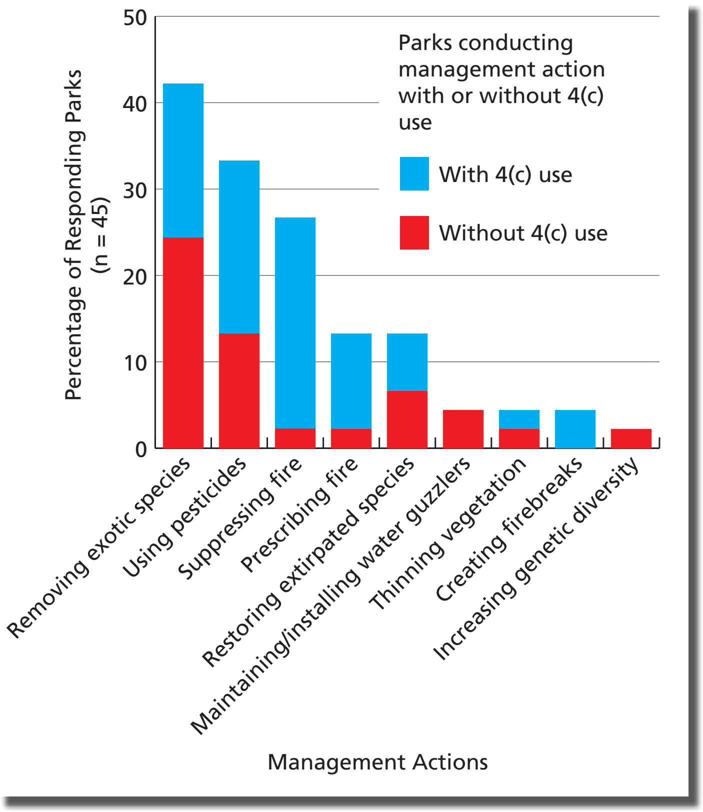


Figure 3. Percentage of parks permitting uses prohibited by Section 4(c)[1] of the Wilderness Act when taking different types of management action in NPS-administered wilderness (n = 45 parks).

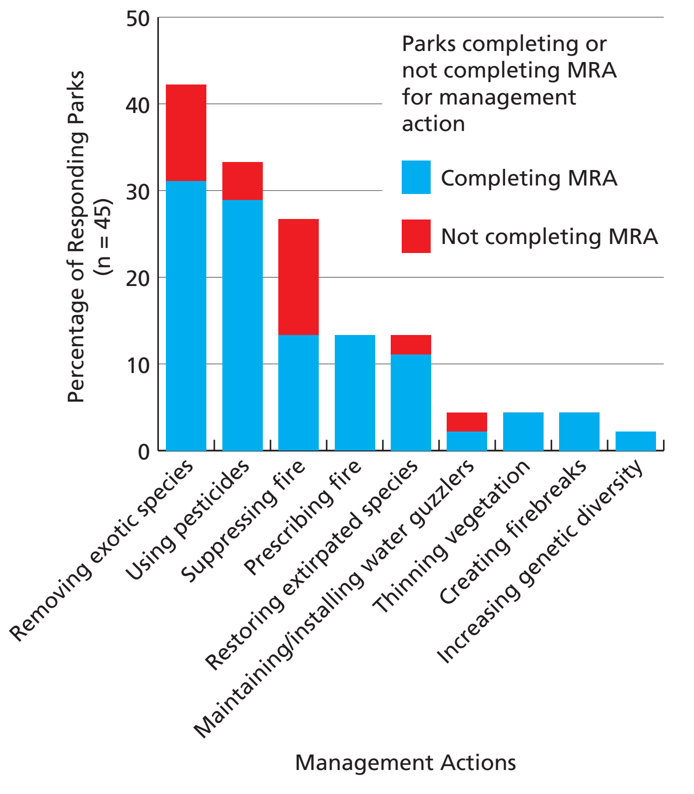


Figure 4. Percentage of parks completing Minimum Requirement Analyses (MRAs)[2] when taking different types of management action in NPS-administered wilderness (n = 45 parks).

use. Prohibited uses were more likely for management activities related to fire. Climate change activities associated with fire allowed prohibited uses 93% of the time. However, these data do not indicate what kinds of prohibited uses were being allowed. Were they using a wheeled cart to carry tools or a helicopter to put out fires? A follow-up study could clarify the degree of intervention.

For the management actions reported by respondents in the study, MRAs had been completed 76% of the time (fig. 4). Whereas completion rates for exotic species hovered near the overall average, those for fire-related activities varied greatly: MRAs for prescribed fire and creation of firebreaks had 100% completion rates while MRAs for fire suppression had been completed about half the time.

Visitor use

Nearly half of respondents described shifts in wilderness visitor use that they attributed to climate change. The most frequently reported shift was a longer visitation season, which was linked to early snowmelt, mild winter conditions, or long open-water seasons. Other parks reported decreases in visitor use attributed to severe storms, fire danger, or hurricane debris.

In response to these shifts, about a quarter of the responding parks had altered their approach to visitor management. Two parks increased wilderness patrols during the traditional shoulder seasons while the others repaired infrastructure impacted by erosion and storms.

Wilderness character

Respondents reported that climate change–driven stewardship activities improved or degraded qualities of wilderness character in complex ways (table 1). Stewardship activities tended to improve the natural quality of wilderness character more frequently than they did other qualities. A handful of respondents expanded wilderness character to include additional benefits outside of the qualities defined in Keeping It Wild. Some respondents concluded that "scientific research" improved wilderness character because it increased knowledge about wilderness and could inform management decisions. Two respondents considered the effect of "enabling legislation" on wilderness stewardship. Enabling legislation includes laws that establish park units or designate

[1]Section4(c) prohibits certain uses except as necessary to manage the area as wilderness. These uses include motorized equipment, mechanical transport, structures, and installations.

[2]MRAs are analyses that guide wilderness managers to preserve wilderness character as they manage designated wilderness. These analyses are required by the National Park Service before management actions are undertaken in designated wilderness.

Table 1. Effects of active stewardship on qualities of wilderness character as reported by 45 units of the National Park System that administer designated wilderness

Quality of Wilderness Character*	Frequency of Parks Reporting Improvements	Frequency of Parks Reporting Degradations
Untrammeled: Unhindered and free from the actions of modern human control or manipulation	1	11
Undeveloped: Retains its primeval character and influence and is essentially without permanent improvement or modern human control or manipulation	9	7
Natural: Its ecological systems are substantially free from the effects of modern civilization	12	4
Solitude or primitive and unconfined recreation: Provides opportunities for solitude or primitive and unconfined recreation	0	9
Other features of value: Unique to an individual wilderness based on features that are in that wilderness. (As stated in the Wilderness Act, wilderness "may also contain ecological, geological, or other scientific, educational, scenic, or historical value.")	1	0

*Quality of wilderness character descriptions are quoted from Landres et al. 2012.

wilderness and often name valued features in the landscape that warrant protection. Some respondents considered preservation of these features as a way to improve wilderness character.

Respondents reported that wilderness stewardship activities degraded many qualities of wilderness character. The untrammeled quality was most frequently degraded. Some respondents volunteered the causes of trammeling: the construction of bridges, removal of invasive and exotic species, planting, rerouting trails, control of fire, installation of monitoring stations, and the use of helicopters. Several respondents reported that stewardship activities had degraded the undeveloped quality (with monitoring activities and installations) and the opportunities for solitude or primitive and unconfined recreation quality (planting, monitoring, flying helicopters, constructing bridges, installing climate change detection equipment, and restricting the use of or closing areas due to severe storms). A handful of respondents also indicated that the natural quality had been degraded by stewardship activities designed to address the effects of climate change in wilderness. Some of these degradations stemmed from installations, aircraft, and bridges. Some respondents described impacts as minor or temporary.

Discussion

The topics addressed by wilderness stewardship activities are complex and often interrelated. One stewardship activity may affect several components of an ecosystem and thus several of the topics examined in this study. Some topics, such as native species, may be more common across parks, and thus more often addressed. Others, such as endangered species, air quality, and water quality, may require attention to comply with legal obligations (e.g., the Endangered Species Act, Clean Air Act, and Clean Water Act). However, the responses in this study reflect topics that elicit stewardship responses in the context of climate change.

These findings highlight climate change–related budget and staffing challenges as well as policy considerations. Many wilderness programs will have to adapt to longer visitor-use seasons. This will have repercussions for visitor centers, permit offices, trail crews, and backcountry patrols. Other wilderness programs may need guidance to balance legal obligations set forth in enabling legislation with those defined by the Wilderness Act.

As more parks consider responding to climate change in wilderness, these findings suggest there may be subsequent repercussions for wilderness character. Choosing to actively manage wilderness may not necessarily be a simple trade-off benefitting the natural quality and degrading the untrammeled one. Several other qualities may be affected as well.

Minimum Requirement Analysis is a tool to help wilderness managers navigate the complicated process of preserving wilderness character. Even though NPS policy requires MRAs for stewardship activities in wilderness, participants in this study indicated that these analyses were ignored a quarter of the time. Some of these actions had to do with suppressing fire. Response to fire may be considered under the Wilderness Act's Section 4(d), Special Provisions. However, NPS Policy 6.3.9 notes that "preplanning is critical to ensure that emergency response incorporates minimum requirements to the greatest extent possible."

Although there are recommended strategies for completing MRAs (see wilderness .net/MRA), there is no standardized MRA methodology required by NPS policy. Without this standardization and a centralized catalog of MRAs, administrative oversight may be lacking.

To ensure that the various qualities of wilderness character are adequately considered in the decision process, it may be prudent to create a database to catalog completed MRAs. As a first step, existing NPS databases that record scientific activities could track whether these activities were occurring in wilderness and whether MRAs had been completed. Cataloging MRA completion rates for other types of wilderness management activities would require an additional database. By tracking this information, these databases would continue to build on the work of the NPS Wilderness Stewardship Division to develop a broader understanding among wilderness managers and park scientists of wilderness and wilderness character. They could also provide a layer of accountability and oversight.

Conclusion

These findings characterize the active approach to wilderness stewardship. They demonstrate that designated wilderness is neither pristine nor free from human activity—whether human-induced climate change or stewardship responses. As such, this study describes the existing relationship between people and wilderness.

Together these data develop a rough sketch for the level and diversity of National Park Service responses to climate change in wilderness. Follow-up studies will be needed to fill out the picture. The data do not indicate the extent of area affected, the frequency of response, or its duration. Nevertheless, these baseline survey data do provide a preliminary sense of the range of topics addressed in wilderness vis-à-vis climate change. Importantly, they demonstrate the number of decision points at which park scientists and wilderness managers opted to actively respond to climate change.

By breaking wilderness character into different qualities, wilderness managers and others can recognize the real and complicated relationship that humans have with nature, wildness, and wilderness. Wilderness character allows us to articulate how stewardship activities may harm some qualities of wilderness while improving others. It also enables wilderness managers to distinguish how management restraint may harm some qualities while improving others. Wilderness character empowers managers and scientists to recognize that restraint is a valid and deliberate approach to the human-nature relationship.

Fundamentally, wilderness character enables us to move beyond generalizing human actions as "good" or "bad" with respect to nature. Rather, it provides the framework through which to recognize, articulate, and study the real and complicated relationship that humans have with nature and wilderness—especially in the context of climate change. Climate change, a phenomenon that operates at a non-park-specific scale, may make NPS response seem insignificant, even arbitrary. However, the response to climate change in wilderness teaches us to recognize the messy, unpredictable, and adaptable nature of the world we live in. It also teaches us that we can tackle the impacts of climate change with thoughtful resolve or we can exercise a deliberate restraint that accepts, mourns, values, and celebrates the world's ability to adapt.

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About the author

Katie Nelson *(katienelson@wrfi.net) has an M.S. in Environmental Studies from the University of Montana. She currently works at the Wild Rockies Field Institute in Missoula, Montana.*

PS

Interpretive Primer

SETH STEIN

Using Lake Superior parks to explain the Midcontinent Rift

By Seth Stein, Carol A. Stein, Eunice Blavascunas, and Jonas Kley

Kayakers paddle past sandstone rocks in Apostle Islands National Lakeshore. Geologists are trying to establish the age of these rocks, which would give insight into how and when the Midcontinent Rift System died.

Abstract

Few areas give interpreters and educators the opportunity to illustrate geoheritage—the role of geology in shaping an area's culture and growth—as well as the Lake Superior region. Lake Superior itself, and the spectacular scenery around it in national, state, and provincial parks, result from a huge geologic structure. Known as the Midcontinent Rift System (MCRS), this structure is a 1.1 billion–year–old, about 1,800-mile (3,000 km) long scar along which the North American continent started to tear apart, but for some reason failed to form a new ocean. The rift gave rise to Lake Superior, which is the basis of the area's water-based history and economy, the copper and building stone deposits that shaped the region's settlement and growth, and today's tourist industry.

Key words

Lake Superior parks, Midcontinent Rift System, mineral deposits, plate tectonics, regional history

SOME OF THE MIDWEST'S MOST spectacular scenery occurs near Lake Superior, in places like Pictured Rocks and Apostle Islands National Lakeshores, Isle Royale National Park, Interstate Park, and Porcupine Mountains Wilderness State Park. These landscapes provide an enormous but underused opportunity for park interpreters and educators to explain some of the most important processes that shape our planet. A crucial aspect of doing this is recognizing that many of the rocks and landforms in the Lake Superior parks are pieces of a huge regional structure. Called the Midcontinent Rift System (MCRS), this structure is a 1.1 billion–year–old, 1,864-mile (3,000 km) long, mostly buried scar along which the North American continent started to tear apart. However, the rifting stopped for some reason and failed to form a new ocean. The MCRS also provided mineral deposits that shaped the region's settlement and growth. Drawing on our experience as researchers and teachers studying the MCRS (Steins and Jonas Kley) and as an interpreter at Isle Royale National Park (Eunice Blavascunas), we seek to give interpreters a brief introduction to MCRS to help them present information to visitors in nontechnical terms about what geologists know already and what they are learning from continuing research. Our goal is to help interpreters visualize and explain how what they see at a specific site fits into an exciting regional picture spanning much of the Midwest and more than a quarter of Earth's history.

Finding the Midcontinent Rift

Many of the rocks around Lake Superior are part of one of the Midwest's most impressive geological features, the long belt of igneous (mostly volcanic) and sedimentary rocks called the Midcontinent Rift System (MCRS) or the Keweenaw Rift (fig. 1, next page). The rift system has two major arms meeting in the Lake Superior region (Hinze et al. 1997; Ojakangas et al. 2001). One extends southwestward at least as far as Oklahoma, and the other extends southeastward through Michigan to Alabama.

Interpreters will find that despite the rift's size, most visitors do not know about it, because these rocks are mostly covered by sediments and sedimentary rocks younger than those of the rift. They appear at Earth's surface only near Lake Superior. One of the best exposures is along the St. Croix River on the Wisconsin-Minnesota border (fig. 2, next page), where the river has cut through a huge stack of lava flows from the rift. Similar flows can be seen in many places, including Isle Royale and the parks along Minnesota's north shore. These flows are billion-year-old versions of modern basalt lava flows that can be seen in Hawaii Volcanoes National Park, or the geologically young (few thousand years) flows at Craters of the Moon National Monument in Idaho. Basalt rock forms from dark, very fluid or "runny" (low-viscosity) lava that typically erupts from hot spot (Hawaii) or rift volcanoes

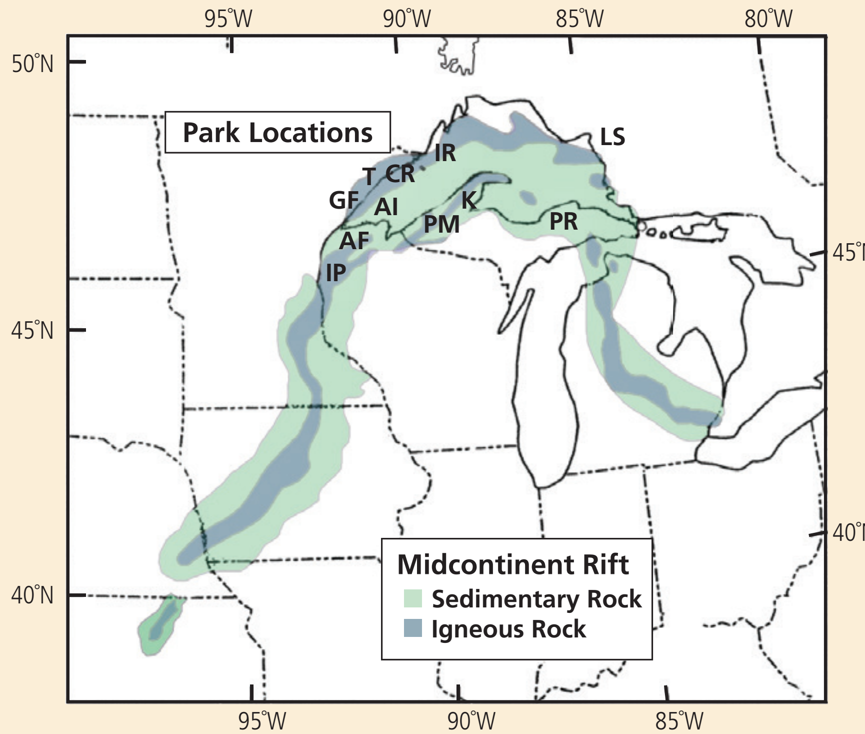

Figure 1. Location and general structure of the Midcontinent Rift, showing some of the parks where rift-related rocks can be seen. Igneous rocks in the rift can be seen at Interstate (IP), Isle Royale (IR), Amincon Falls (AF), Gooseberry Falls (GF), Tettegouche (T), Cascade River (CR), Lake Superior (LS), and Porcupine Mountains (PM) parks. Sediments deposited after the volcanism can be seen at Apostle Islands (AI) and Pictured Rocks (PR) National Lakeshores. The history of copper mining in the rift rocks is presented at Keweenaw National Historical Park (K).

and flows out on Earth's surface before it solidifies.

Geologists combine what they learn from the exposed rocks with clever techniques that allow them to "see" the deeply buried parts of the rift. One technique uses very accurate measurements of gravity and magnetism (fig. 3). The buried volcanic rocks contain lots of iron, and so are denser and more magnetic than the surrounding rocks. These can be detected by gravity surveys that use equipment like a super-precise bathroom scale, and magnetic surveys that use equipment like a super-precise metal detector. Surveys have mapped a huge thickness—up to 15 miles or 25 km—of volcanic rocks, so the entire rift system has more than 240,000 cubic miles (a million cubic kilometers) of volcanic rocks. This is 44 times the volume of all the Great Lakes combined!

Other methods use seismic waves, vibrations traveling through rock, to visualize at depth. This method, which is also used to

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Figure 2. Basalt flows form cliffs at Interstate Park along the St. Croix River, Wisconsin.

find oil and natural gas deposits, is like the way doctors use ultrasound to see inside patients. Surveys across Lake Superior (fig. 4) used seismic waves generated by a sound source towed behind a boat (Green et al. 1989). The seismic waves travel downward, reflect off interfaces at depth between different rocks, and return to the surface. The reflected waves are detected by seismometers at the surface, and computers generate graphics called "seismograms" that provide an image of deeply buried rock layers. A north-south cross section compiled from seismograms shows a deep depression under Lake Superior filled by layers of volcanic rocks and overlying

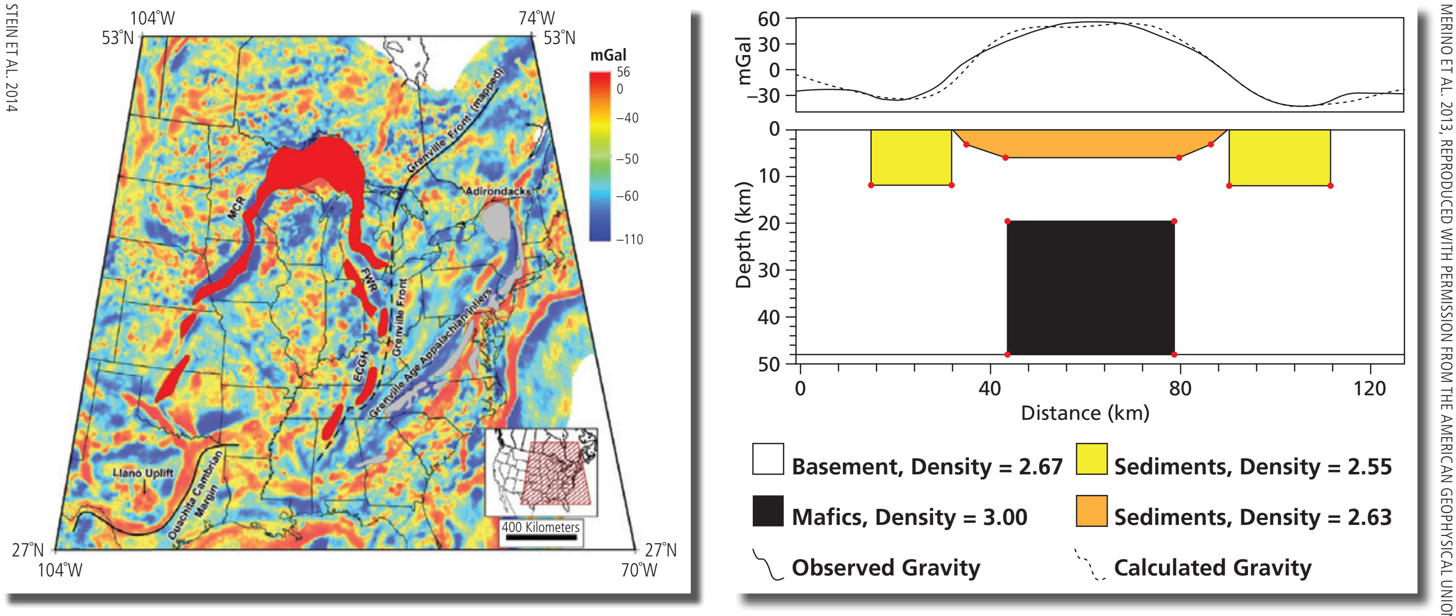


Figure 3. The gravity map on the left shows the Midcontinent Rift (MCR) and its continuations along the Fort Wayne Rift (FWR), and East Continent Gravity High (ECGH), indicated by high values (red). The conceptual model on the right shows a cross section of the MCR, illustrating how dense igneous rocks at depth (black rectangle) cause stronger gravity at the surface. The density of the rocks is given in g/cm^3 and the gravity effect of the rocks is measured in milligals (mGal), which are about a millionth of Earth's average surface gravity.

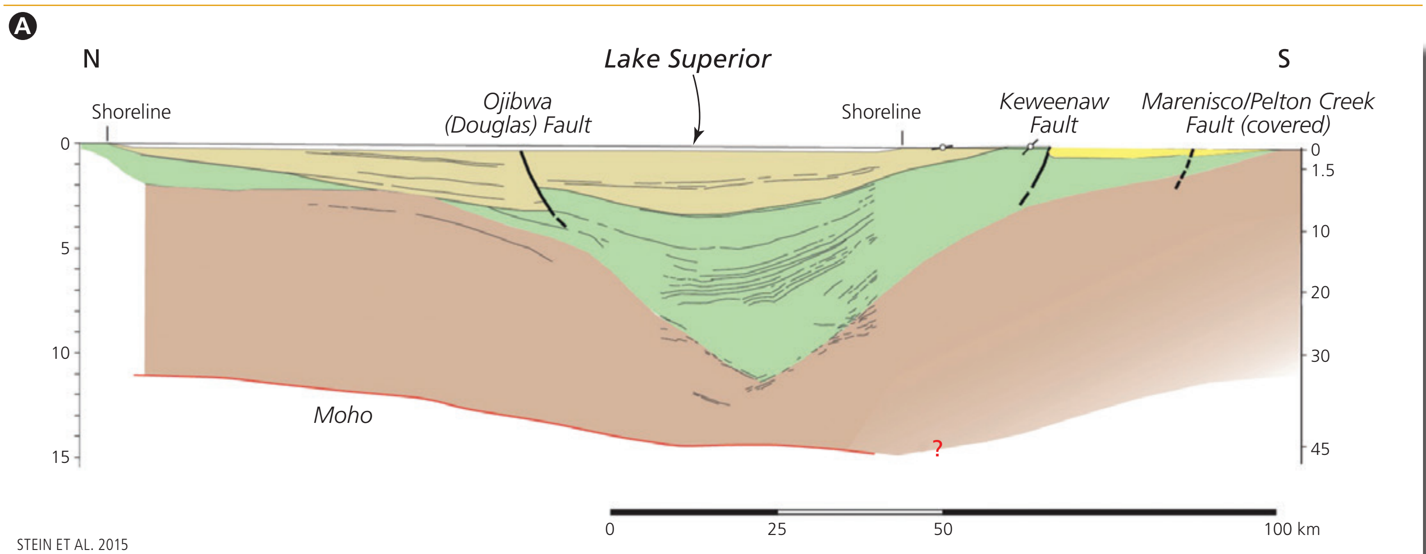
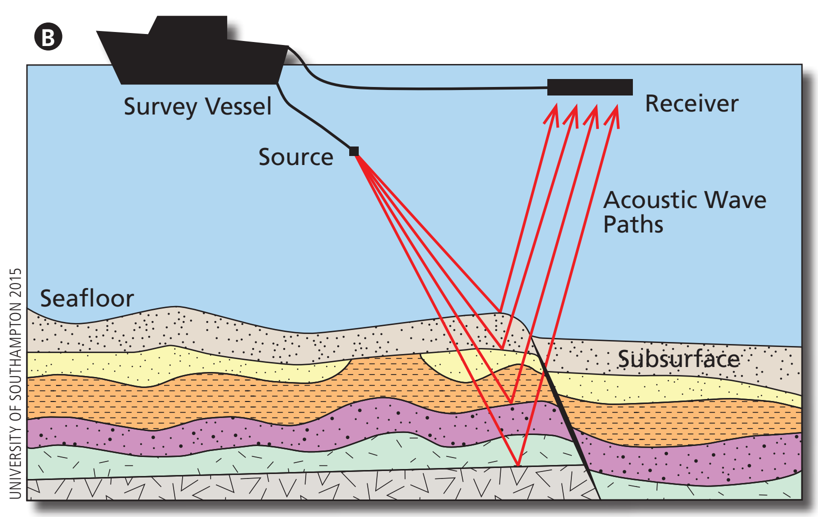


Figure 4. The illustration (A) is a cross section below Lake Superior drawn from seismic reflection profile data, showing the U-shaped rift filled by volcanic rocks (green) and overlying sediments (tan). At the right (B) the illustration shows how seismic reflection profiling works.



sediments to a depth of 18 miles (30 km), which is much deeper than Lake Superior's average depth of about 500 feet (150 m). This structure is a "U-shaped" type of fold called a syncline. The volcanic rocks and associated sediments on the north side—as seen at Isle Royale—dip southward toward the center of the lake, whereas those on

SETH STEIN (2)

Figure 5. MCRS rocks on either side of the syncline are shown in the photos. (Left) North-dipping sediments near Copper Harbor, Michigan, on the Keweenaw Peninsula. (Right) South-dipping basalt flows near Rock Harbor, Isle Royale National Park.

the south side—as seen in the Keweenaw Peninsula—dip to the north (fig. 5).

More recent studies are using data from the National Science Foundation's Earth-Scope program (http://www.earthscope.org/). One component of EarthScope is the transportable array of 400 seismometers installed at sites about 45 miles (70 km) apart, extending across the United States from north to south. After two years at a site, each instrument is picked up and moved to the next location on the eastern edge of the array, so the array moves across the country. In addition, a network of seismometers called SPREE (Superior Province Rifting EarthScope Experiment), operated by Northwestern University, Washington University in St. Louis, the University of Minnesota, the University of Manitoba, and the University of Quebec at Montreal, recorded data for two years across and along parts of the rift (fig. 6). These studies' goal is to see how the rift area differs at depth from its surroundings (Shen et al. 2013) and thus how the deeply buried rocks record the events that formed the rift. Other ongoing research includes further gravity studies by researchers from the University of Oklahoma and studies of the electrical properties of the rift rocks by researchers from Oregon State University and the University of Utah.

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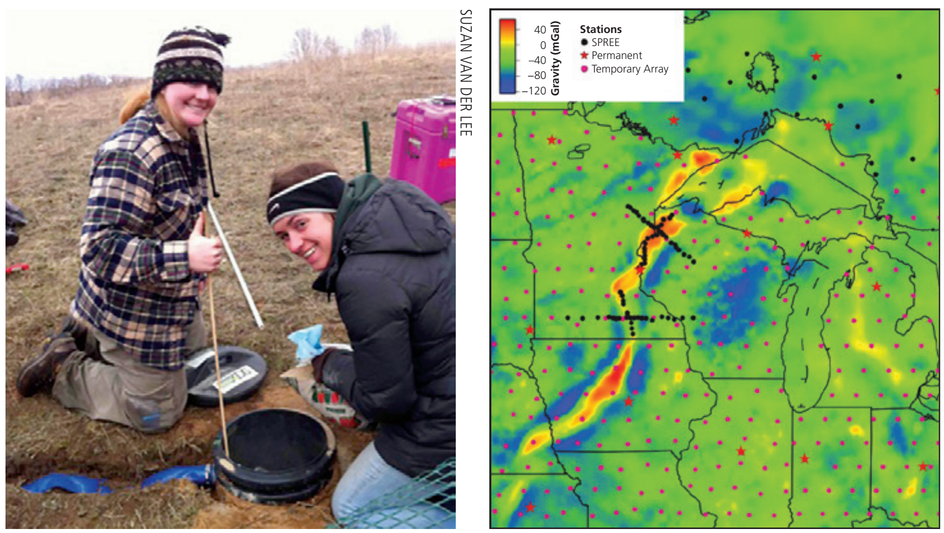
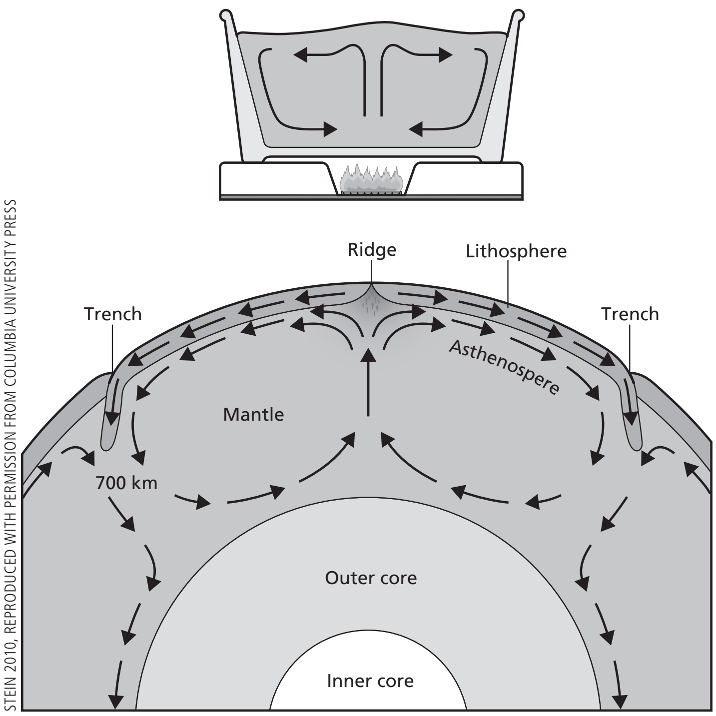


Figure 6. (Left) Northwestern University graduate students Emily Wolin and Jessica Lodewyk install a temporary SPREE seismic station in northern Wisconsin. (Right) The gravity anomaly map of the Midcontinent Rift region also shows the locations of permanent (stars), transportable array (red dots), and flexible array seismic stations (black dots) being used in SPREE.

How old is it?

The volcanic rocks in the rift are about 1,100 million, or 1.1 billion, years old (Davis and Green 1997). These dates come from measuring the concentration of isotopes of radioactive elements that decay into other isotopes. This method is like the carbon-14 dating used by archaeologists to study artifacts from ancient civilizations, but uses minerals containing uranium and lead isotopes that have much longer half-lives to date much older rocks. Their age, 1.1 billion years, is about a quarter of the age of Earth, 4.6 billion years. This time is during the Mesoproterozoic Era (1.6–1



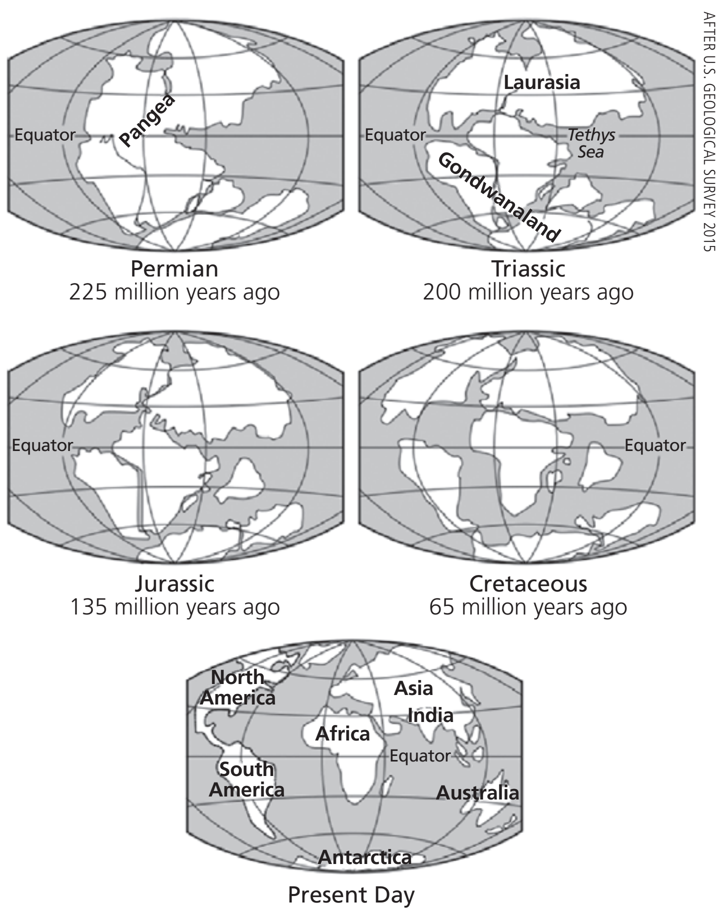


Figure 7 (top). An ideal convection cell is illustrated by a pot of boiling water on a stove. (Bottom) Plate tectonics results from convection in Earth's mantle. The real pattern is more complicated than this ideal picture.

Figure 8 (right). Reconstruction of Pangaea and the motions of the continents since its breakup.

billion years ago), during which the most complex organisms included multicellular algae. It is long before dinosaurs appeared, about 230 million years ago.

Rifts and plate tectonics

The Midcontinent Rift demonstrates important aspects of the fundamental concept of modern geology, plate tectonics, which explains how Earth works and why it differs from our neighboring planets. The key aspect of plate tectonics is that Earth's outer shell consists of continent- and ocean-sized moving plates of relatively cold, strong rock, about 60 miles (100 km) thick, that move relative to one another at speeds of a few inches per year—about the speed fingernails grow (fig. 7). This shell is called the lithosphere. The strong plates slide over warmer and weaker rocks below called the asthenosphere.

Plates are pretty rigid, which means that their insides do not deform much. Instead, almost all the geological action happens at the boundaries between plates, like the San Andreas Fault. These are where most earthquakes and volcanic eruptions occur and where mountains are constructed. Plates are like ice chunks floating around on water, sliding by and banging into one another.

What happens at the boundary between two plates depends on the motion between them. At divergent boundaries, such as a mid-ocean ridge or continental rift, plates move away from each other, whereas at convergent boundaries they move toward each other. At the third type, transform fault boundaries, plates slide by each other. For example, earthquakes happen on California's San Andreas Fault because it is part of the transform boundary between the Pacific and North American plates.

To see how plate tectonics works, think of heating a pot of water on a stove. As the water on the bottom gets hotter, it expands, becomes less dense, and rises to the top. Once it gets there, it cools, becomes denser, and sinks. This process of hot fluid rising and cold fluid sinking is called convection. Plate tectonics is a more complicated version of this simple convection system. Mid-ocean ridges are upwelling areas where hot material rises from the deep mantle and cools to form cold, strong plates. Subduction zones are downwelling areas where plates are consumed as their cold material sinks, heats up, and is mixed back into the mantle.

The heat causing convection is partly left over from when the planet accreted from a dust cloud and partly from the decay of radioactive elements. Earth still has enough heat for active convection, but Mars—which is much smaller, about the size of Earth's core—has cooled too much for active plate tectonics.

Because plates move relative to each other, their geometry changes with time. Continents come together to form supercontinents—such as Pangaea 225 million years ago (fig. 8, previous page)—that later split apart in a process called rifting. A successful rift evolves into a new mid-ocean ridge that creates a new ocean basin between

Figure 9. Samples of basalt (left) and granite (right).

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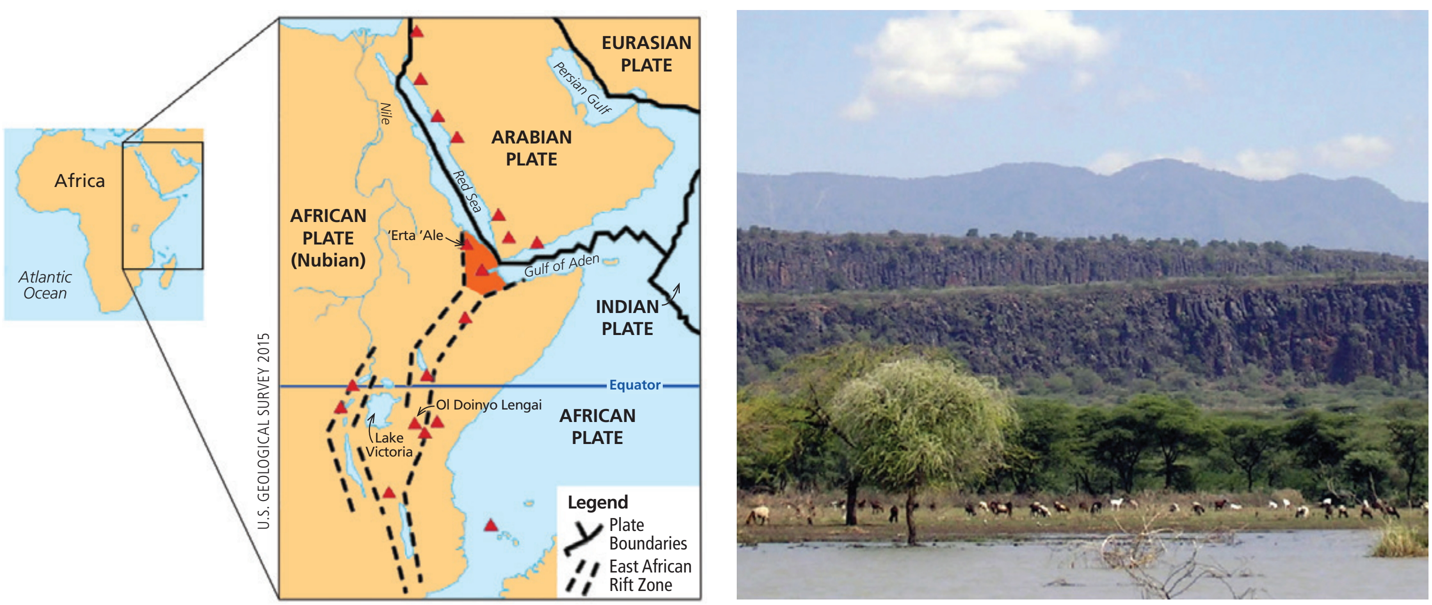
the pieces of continent. However, some rifts fail, because rifting stops before a new ocean basin forms. The MCRS is a very old rift that failed to split North America 1.1 billion years ago.

The creation of ocean basins between continents occurs because rocks of Earth's crust under continents are different from those under the oceans. Crust under the continents is pretty much like granite, the light-colored rock in figure 9. Granite is exposed in places like Yosemite National Park in California, Mount Rushmore National Memorial in South Dakota, and Missouri's Saint Francis Mountains. When these rocks are eroded by rain, wind, and ice, the sediments that result are carried by rivers and end up in places like beaches, giving us the beautiful white sand along the Great Lakes' shores. Some of this sand turns into the sandstone rock that appears in many places in the Midwest.

In contrast, the crust under the oceans is mostly basalt, the darker rock in the picture. Basalt is the volcanic rock that forms plates at mid-ocean ridges. It is not as common on the continents as granite, but there is some. Basalt lava flows fill the Midcontinent Rift, as shown by the cliffs along the St. Croix River (see fig. 2), on Isle Royale (see fig. 5), and along the shores of Lake Superior.

Granite and basalt have different colors because they have different chemistry. Granite contains mostly the elements silicon and oxygen, while basalt has less of these and more iron and magnesium. That difference makes granite about 15% less dense than basalt, which means that a chunk of granite weighs about 15% less than a chunk of basalt of the same size.

This density difference has a huge consequence for how Earth works. Because the continents are made up of less dense granite, they "float" higher than the denser basalt under the oceans, just the way wood floats in denser water. For the same reason, the rocks forming the continents do not sink into the denser mantle at subduction zones, so continental rocks stay at the surface much longer than oceanic rocks. That is why oceanic lithosphere is never more than 200 million years old, but billion-year-old continental rocks are found in the Midwest.



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ALEX GUTH

Figure 10. (Left) Geometry of the East African Rift. Triangles indicate active volcanoes. (Right) The East African Rift in Kenya. The MCRS looked similar before it was filled by sediment, but its volcanic rocks can be seen in some places today (see figs. 1, 2, and 5).

Continental rifting

To understand how plate tectonics operates, geologists use one of their most powerful methods: visualizing how features formed in the past by looking at places where similar features are forming today. Geologists often say "the present is the key to the past." That is nice because it is a lot easier to see the present. For example, if we did not know how people grew up, we could get a good idea by looking around and seeing babies, toddlers, children, teenagers, young adults, and older adults.

To study how the Midcontinent Rift formed more than a billion years ago, we can look at a similar feature that is active today. For example, the East African Rift is splitting up Africa, forming the huge rift valley and causing volcanoes like Mount Kilimanjaro. The rift system is dividing Africa into two plates and rifting Arabia away from it, forming new ocean basins in the Red Sea and Gulf of Aden between the landmasses (fig. 10). That is how the Midcontinent Rift looked 1.1 billion years ago. Of course, there were no lions, giraffes, trees, or even grass—because they had not evolved yet.

The East African Rift is in the early stages of the life cycle that continents and oceans go through, called the Wilson cycle (fig. 11). It begins when part of the continent starts to be pulled apart. The process involves heating from below, but geologists still do not know exactly why and how. The granite crust stretches like taffy and starts to break along newly formed faults, and a rift valley forms as earthquakes move blocks of crust downward, while the material below flows sideways. It is like what happens if you pull both ends of a candy bar that has an outer chocolate shell and a nougat interior: the chocolate layer breaks and the inside stretches and bends downward (fig. 12).

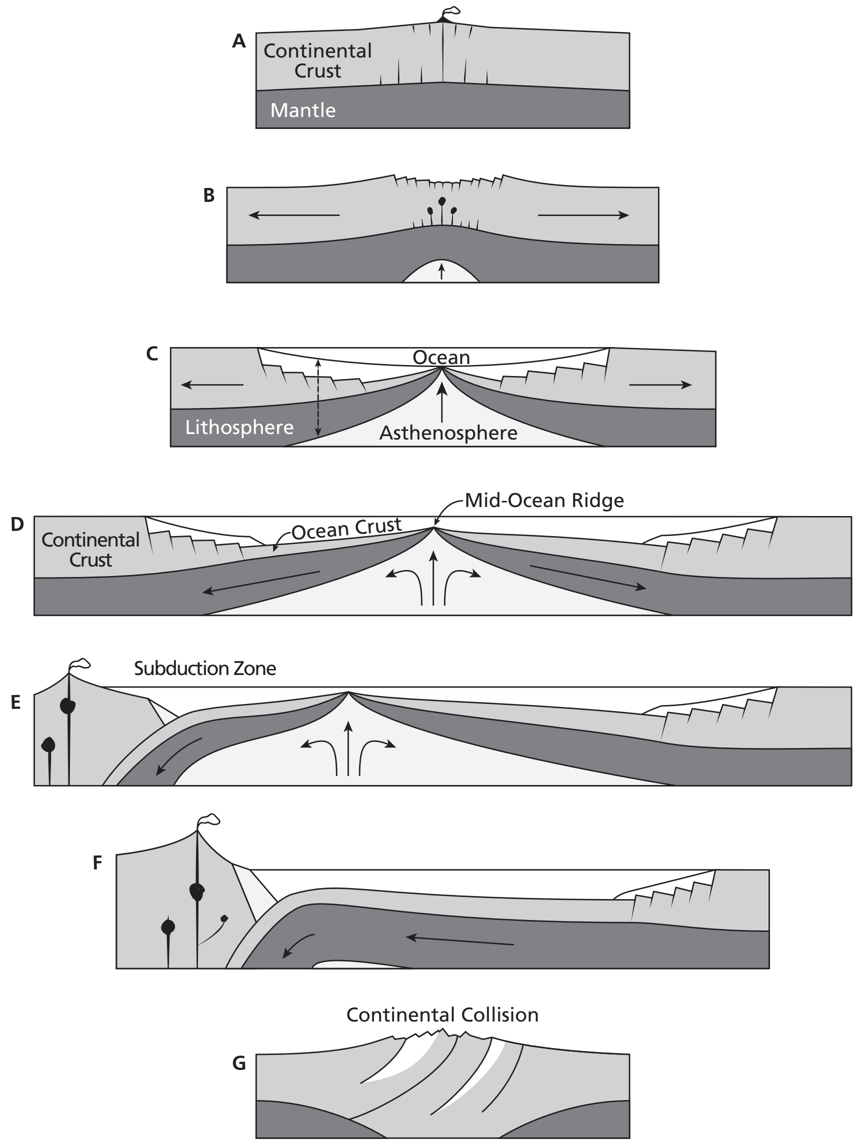

Figure 11. The Wilson cycle shows the stages through which the continents and oceans evolve. (A and B) Continental stretching and rifting; (C) seafloor spreading begins, forming a new ocean basin; (D) the ocean widens and is flanked by sedimented passive margins; (E) subduction of oceanic lithosphere begins on one of the passive margins, (F) so the ocean basin gets smaller. Eventually, the ocean basin is all subducted away and the continents collide, building a mountain range (G).

Figure 12. A candy bar shows how rifts work: when the bar is pulled apart, the top layer breaks and the lower layer stretches.

Scenery around Lake Superior records the geologic events 1.1 billion years ago that shaped the area and influenced the region's settlement and growth.

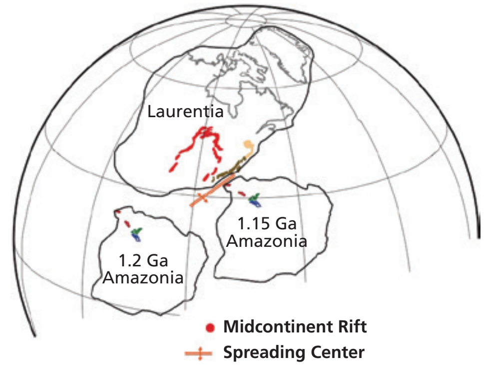

Figure 13. Reconstruction of plate positions 1.2 and 1.15 billion years ago showing the history of Amazonia rifting away from Laurentia. "Ga" denotes a billion years before the present. Although most rocks that old are buried beneath younger ones, some that record these events, marked by colored symbols at locations shown on either side of the opening ocean that are now thousands of miles apart, have been found. These matching rocks were used to reconstruct this history.

If the rift keeps opening, hot material from the mantle rises under the rift and causes volcanoes where basalt magma erupts, as is happening today along the East African Rift—and as happened a billion years ago along the MCRS. Eventually the rift valley is filled by enough basalt that it becomes an oceanic spreading center. Spreading at the new ridge forms a new ocean that separates the continental rock on both sides. With time, the ocean widens and looks like the Atlantic does today. Because the ocean cannot keep getting wider forever, eventually a new subduction zone forms, the entire ocean basin becomes closed, the continents on either side collide, and the cycle ends. Some time later, it starts again, so Earth's history has many cycles of continents rifting to form new oceans that eventually close.

However, sometimes rifting goes on for a while and then stops, failing to split the continent, and leaving behind a "failed rift," a long valley of stretched and faulted rock that eventually gets filled up with sediments and buried. That is what we see today in the Midcontinent Rift.

Ongoing research

Although geologists know a reasonable amount about the MCRS, there is a lot more to be learned. Current research addresses three major questions: how did it form, how did it evolve, and how did it fail? None of these are fully answered yet, but new data and ideas are giving additional insight.

Detailed mapping of the underground Midcontinent Rift using gravity data shows that the rift extends much farther than had been previously thought (Stein et al. 2014). Thus, although the MCRS is now in the middle of the continent, it formed at the edge of a larger continent. As continents form and break up, different pieces of the continents are grouped in different ways. Their positions can be figured out because, when volcanic rocks solidify, they record Earth's magnetic field, which depends on latitude (Swanson-Hysell et al. 2014).

The MCRS probably formed as part of the rifting of a continental piece called Amazonia (now in northeastern South America) from the continent of Laurentia (now central North America) (fig. 13). Once the seafloor was spreading and a new ocean began forming, the MCRS—the remaining piece of the rift system—shut down, leaving a failed rift. We do not know how this happened, where the hot material came from, or why this process ended. One possibility is that the rocks came from a hot spot, a volcanic region in the middle of a plate like that now under Hawaii (Hutchinson et al. 1990; Nicholson et al. 1997; Miller 2007). We hope that ongoing research will help answer these questions. Although the present Lake Superior was sculpted by much more recent glaciers—most recently about 10,000 years ago—its location reflects the geometry of the ancient rift below it (see fig. 3), because the soft sediment filling the rift was easier to erode than basalt.

How all this happened is an active research area. Figure 14 shows a schematic view of our current idea of the sequence of events. The rift formed by extension, with rocks above the major faults moving downward. Geologists call this "normal" faulting (fig. 15). Volcanic rocks filled the resulting depression. After the rifting stopped and the faults became inactive, huge additional thicknesses of volcanic rocks were deposited, and the cooling crust subsided. Once the volcanism ended, thick sediments filled the valley above the lava flows. After subsidence ended, beautiful flat-lying sediments seen in places like Apostle Islands National Lakeshore (page 19) were deposited. Eventually the area was compressed, and the faults that formed during extension and along which the central rift subsided moved the other way. The faults thus went from having "normal" motion during extension to having "reverse" motion during compression

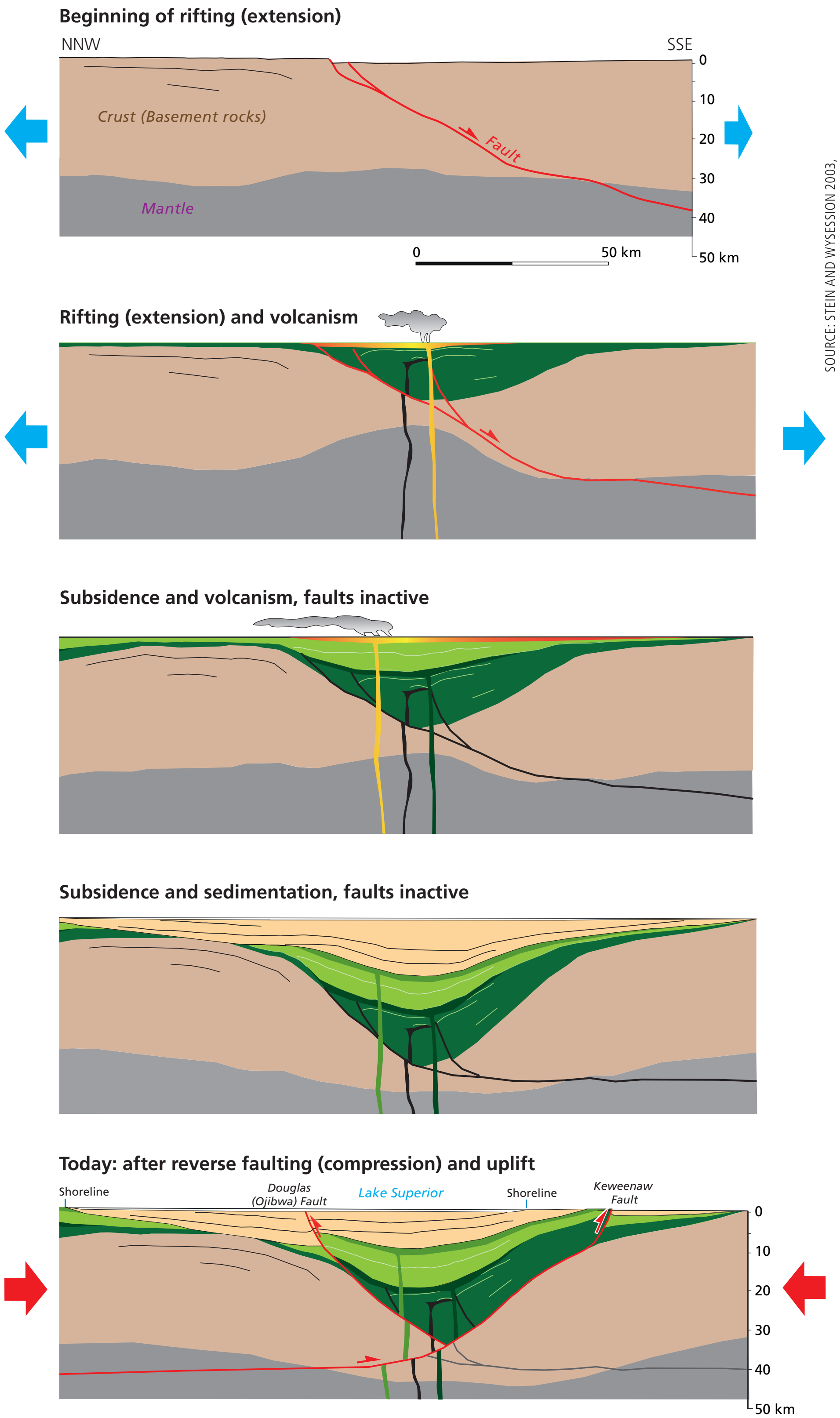

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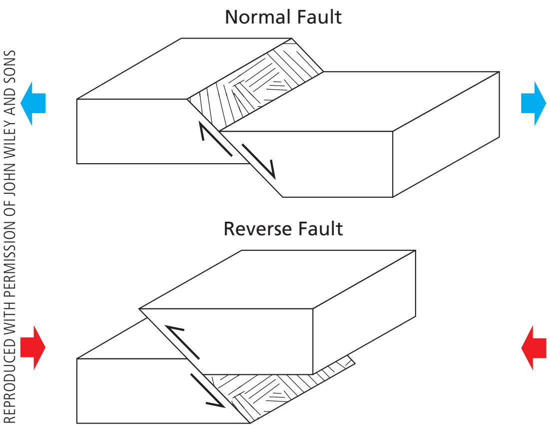
Figure 14. Schematic view of the sequence of events that formed the Midcontinent Rift, leading to the structure seen today (fig. 4A). Extension is shown by blue arrows, and compression by red arrows.



SOURCE: STEIN AND WYSESSION 2003, REPRODUCED WITH PERMISSION OF JOHN WILEY AND SONS

Figure 15. Comparison of the normal sense of motion on faults that occurs during extension, shown by blue arrows, with the reverse motion that occurs during compression, shown by red arrows.

(fig. 15). The reverse motion on faults like those on either side of Lake Superior (see fig. 14) uplifted the volcanic rock, which is why we see it at Earth's surface today.

How the MCRS shaped the area's growth

Lake Superior is located above the Midcontinent Rift, so the rift provided the region's first transportation system, which is still crucial today. European settlers and traders used the lake to import and export trade goods, lake fisheries were significant first commercially and now recreationally, and the lake remains an economic engine today. The Port of Duluth-Superior, by far the largest and busiest on the Great Lakes, handles an average of 38 million tons (34 million metric tons) of cargo and nearly 1,000 vessel visits each year, connecting the heartland of the United States and Canada to the rest of the world. The lake also generates water-oriented tourism.

The MCRS also provided mineral deposits that shaped the region's settlement and growth. Hot water rising through the rift's volcanic rocks dissolved copper and deposited it in concentrations that became sources of valuable ore in many places around Lake Superior. For at least the past 7,000 years (Martin 1999; Pompeani et al. 2014) American Indians mined copper and traded it as far south as Illinois, as shown by archaeological studies in Cahokia, Illinois. The discovery of commercially viable copper deposits in the Upper Peninsula of Michigan during the 1840s led to a mining boom that shaped the area's economy (Bornhorst and Barron 2011). In the late 1800s, MCRS sandstone was quarried along the lakeshore and exported as building stone throughout the upper Midwest, primarily via Lake Superior shipping (Eckert 2000).

See the Midcontinent Rift

Rocks around the Lake Superior region record different aspects of this story. For example (fig. 1):

- Lake Superior fills the deep basin left over from the rifting and is the best place to seismically "see" the rocks at depth (see fig. 4).
- Interstate Park, Saint Croix National Scenic Riverway, Isle Royale National Park, Porcupine Mountains State Park, and parks along Minnesota's north shore show the volcanic flows that tell geologists when and how they erupted.
- Apostle Islands and Pictured Rocks National Lakeshores show sediments deposited after the rifting that scientists are trying to use to learn when and how the volcanism ended.
- Keweenaw National Historical Park presents the history of copper mining from the rift rocks and its effects on the area's development, and Michigan Tech's A. E. Seaman Mineral Museum shows spectacular examples of the copper.

Acknowledgments

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A digital presentation and HTML version closely related to this article, together with other information, are available online at http://www.earth.northwestern.edu/people/seth/research/mcr.html. In addition to many scientific articles, sources including those listed below present more detailed and site-specific information. Keweenaw National Historical Park, the Keweenaw geoheritage program (http://www.geo.mtu.edu/KeweenawGeoheritage/KeweenawGeoheritage/Welcome.html) and the proposed upper peninsula Geopark (http://www.geo.mtu.edu/~raman/Geopark/Welcome.html), and the NSF EarthScope program provide additional resources.

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About the authors

Seth Stein *is William Deering Professor in the Department of Earth and Planetary Sciences, Northwestern University, Evanston, Illinois. He can be reached at seth@earth.northwestern.edu.* ***Carol A. Stein*** *is professor in the Department of Earth and Environmental Sciences, University of Illinois at Chicago.* ***Eunice Blavascunas*** *is assistant professor of Environmental Studies and Anthropology at Whitman College, Walla Walla, Washington. She was the district interpretive park ranger for Isle Royale National Park in 2001, conducted a social study of science there in 2003, and worked as an interpretive ranger at Yosemite (2008, 2009) and Canyonlands (1990) National Parks.* ***Jonas Kley*** *is professor of geology at the Georg-August Universität, Göttingen, Germany.*

Research Reports

Satellite communications: Geocaches as interpretation

By Larry Perez and Rudy Beotegui

Abstract

Although geocaching is experiencing rapid growth in popularity, the National Park Service has generally been cautious about allowing it as a visitor activity. In 2012, Everglades National Park initiated a robust, yearlong pilot program to assess the efficacy, reach, and impact of geocaching as an interpretive tool. The program garnered significant use, revealed potential for reaching diverse audiences, demonstrated success in advancing interpretive goals, and resulted in limited physical impact on cache locations. The results of this project suggest that parks and visitors may derive mutual benefit from the development of interpretive geocache programs.

Key words

Everglades, geocaching, interpretation

GEOCACHING CAN GENERALLY BE DESCRIBED AS A location-based recreational activity that employs the Global Positioning System (GPS). Using a set of furnished coordinates, participants ("geocachers") use GPS-enabled devices to locate objects hidden by fellow participants (Groundspeak, Inc. 2013). The coordinates for these objects ("geocaches") are typically disseminated via public Web sites. Participants document each find online, amassing a record, or "cache log," of their geocaching activity over time. Geocaching.com serves as the primary clearinghouse for the activity and—at the time of this writing—lists more than 2.5 million active geocaches, and estimates there are more than 6 million geocachers worldwide (Groundspeak, Inc. 2014).

The most common type of geocache is a single hidden physical container (fig. 1). Over the years, however, geocaches have evolved into several variants, including multistage caches, puzzle caches, and letterbox hybrids (which incorporate the use of clues in addition to coordinates). At a minimum, most cache containers are usually stocked with a pen and logbook (which serves as a guest book, of sorts) and a variety of inexpensive trinkets that visitors are free to trade. Though containers are intended to be readily accessible to searchers, they are typically camouflaged and well hidden beneath structures, rocks, or vegetation to prevent casual detection. Some caches lack containers altogether and instead direct participants to social gatherings, GPS-enabled games, volunteer events, or educational opportunities.

Applied experience with geocaching reveals that the activity can serve purposes beyond simple recreation. Various organizations have used it as a means of cultivating tourism, using caches to highlight unique environmental, historical, or cultural assets sometimes overlooked by area visitors (Boulaire and Hervet 2012). In the realm of formal education, geocaching has been used in both primary and secondary school settings as a means of engagement on topics of geography (Paulus et al. 2007) and mathematics (Bragg et al. 2010), as well as to promote physical exercise.

NPS PHOTO

Figure 1. Weatherproof plastic boxes provided an inexpensive solution for caches placed in Everglades National Park.

Geocaching in the national parks

Some have suggested that—given its conceptual resemblance to modern-day treasure hunting—geocaching can be a logical avenue by which to introduce tourists to the tangible and intangible treasures that await their discovery (Boulaire and Hervet 2012). This idea has particular relevance for interpretation in national parks, which endeavors to facilitate connections between park visitors and the resources they come to see. Nonetheless, the National Park Service (NPS) has generally proceeded with caution in permitting geocaching on its lands, and the activity has, to date, not been widely accepted.

Current NPS management policies help define appropriate visitor uses in national parks, and provide guidelines for the protection of natural, cultural, historical, and wilderness resources (NPS 2006). Though these policies highlight issues of concern relative to geocaching, the policies do not expressly forbid the activity. Rather, they include provisions allowing for a wide variety of public uses, provided they are consistent with a park's purpose and do not result in unacceptable impacts. In 2009 the National Park Service issued policy guidance specifically addressing geocaching and other forms of GPS-based recreation. Citing the great diversity among units of the National Park System, this guidance acknowledged that location-based activities may be appropriate in some areas, and granted superintendents the authority to "make determinations on a case-by-case basis" (NPS 2009).

Having recognized the longevity and growing popularity of geocaching, some national park sites have sought to capitalize on a perceived opportunity to engage a particular segment of park visitors (Reams and West 2008). To do so, a handful of parks have introduced park-sponsored caches, which in most cases are owned and managed by the park as an officially sanctioned educational visitor activity. These parks have adopted a series of strategies regarding cache type and placement to address concerns about potential impacts, and employ adaptive management to address problems should they arise. These early programs have illustrated some of the potential benefits to be had by engaging the geocaching community, and serve as a model for the program described herein (Reams and West 2008).

Methods

Everglades National Park (hereafter "Everglades") initiated a one-year pilot project to gauge the impacts and efficacy of physical geocaches as a communication and interpretation tool (fig. 2). Park interpretive staff (including the authors) developed a total of five physical geocaches and deployed them inside the boundaries of the park in January 2013, and closely monitored their usage throughout the trial period. All caches were located along trails and improved surfaces along the main park road. We determined site selection in consultation with interpretive, law enforcement, and maintenance personnel overseeing each locale. Caches ranged in distance from 0.25 to 38.0 miles (61 km) from the southernmost entrance of Everglades. We used multiangle photography to document site conditions at each selected location prior to cache placement.

NPS PHOTO

Figure 2. Park Ranger Larry Perez discusses the Employee for a Day Geocache Trail with a visitor along the Anhinga Trail in Everglades National Park.

Figure 3. A site bulletin was created to accompany each cache. Four of the five bulletins encouraged participants to assume the role of a different park employee.

Cache descriptions and coordinates were published on both Geocaching.com and the Everglades Web site. Because these five caches occurred along a linear feature explored in its entirety by many visitors, we decided to develop these caches as a cohesive "geocache trail." Thus, the caches shared a common theme: each cache encouraged visitors to assume the role of a different park employee. Four of the five caches introduced participants to a specific member of the park team and a real-world management challenge he or she faced. This information was conveyed through both the online cache description and a series of site bulletins specifically developed for distribution via each cache (fig. 3). A summary of this content is provided in table 1 (next page).

Table 1. Summary of Everglades National Park cache locations and themes

Cache Location	Park Employee Featured	Park Issue Highlighted
Ernest Coe Visitor Center, Main Entrance	None	Cache served as introduction to series
Anhinga Trail, Royal Palm Visitor Center	Park Ranger	Potential human-animal conflict between alligators and visitors along popular Anhinga Trail
Old Ingraham Highway, Research Road	Park Botanist	Ongoing infestation of invasive Brazilian pepper and limitations of present control techniques
Deer Hammock, Main Park Road	Park Fire Management Officer	Threat posed by wildfire to nesting colony of endangered Cape Sable seaside sparrows
Visitor Campground, Flamingo	Park Superintendent	Destruction of Flamingo structures by hurricanes, and realities of rebuilding in light of sea-level rise

We designed the caches to encourage introspection and solicit feedback from participants, building on the increasingly popular use of facilitated dialogue as an interpretive technique (Abram 2007). In both the online cache description and each site bulletin, participants were specifically invited to leave their thoughts as to how they would deal with each issue while logging their finds on Geocaching.com. Participants were also invited to learn how the park has actually responded to each issue by visiting custom-crafted Web pages for each cache, which could be accessed either from a link in the online cache description or via a quick response (QR) code on the accompanying site bulletin.

Once the caches were in place, park staff maintained them over the course of a full year, and recorded all related online activity.

Figure 4. Families and travel companions often geocache together, complicating exact estimates for total visitor use.

IMAGE COURTESY GEOCACHING.COM

Results

We evaluated the pilot project across five criteria: overall use, geographic reach, desired level of engagement, QR code use, and site impacts from visitor use. The results of each evaluation metric follow.

Overall use

To compile usage statistics, we reviewed participant cache logs created and hosted on Geocaching.com. These online logs are used to record when a particular cache was successfully found (or not found). Log entries also provide an opportunity for participants to submit photos and open-ended comments about the experience. These logs are informal, entirely voluntary, and are submitted using the participant's Geocaching.com username.

Each geocache also contained blank logbooks in which participants could physically record their find.[1] Information recorded in these logbooks generally mirrored that posted online. Though additional visitation statistics might have been gleaned from reviewing these logbooks, they were not included in our analysis for several reasons—most notably, the loss of some due to theft and flooding.

A total of 1,403 unique visitor contacts were made across all five caches. The number of unique visitor contacts was derived from qualitative information contained in the cache logs, such as references to family members, use of plural pronouns, and submitted photos (fig. 4). Usage statistics, therefore, should be considered conservative estimates, because individuals do not always volunteer information about travel companions or group size.

The five cache locations yielded an average of 281 unique visitor contacts, with an average of 1.47 contacts per logged visit. Cache use was significantly higher at areas of high visitor use (i.e., visitor centers and popular trails) than in more remote or less traveled areas.

Geographic reach

We reviewed online cache logs to gain insight into use of caches by domestic and international visitors. Out of 952 total cache logs, 179 (18.8%) held explicit information regarding a visitor's place of

[1] Blank logbooks are recommended in part to ensure that a park does not intentionally collect any personally identifiable information (PII) or appear to be conducting a survey.

origin. These logs included representation from 10 U.S. states and 13 countries. Figure 5 illustrates the proportion of cache visitors by nationality, as reported through cache logs.

Accurately assessing the true demographics of cache users is impossible from the present data set, as most visitors did not feel compelled to disclose their area of origin. These data are of interest, however, in beginning to understand the potential reach of, and principal audiences for, this type of activity. The information provided reflects an overwhelmingly large proportion of users from Europe (71%) and North America (26%).

Desired level of engagement

In four of the five caches placed in Everglades, a site bulletin encouraged visitors to consider a real-world problem facing park managers and to weigh in on how they might remedy the situation while logging their cache. We reviewed all logs across these four caches (n = 667) to assess how many had endeavored to answer the question, thereby reaching our desired level of engagement.

Of the logs we reviewed, 129 (19.3%) contained opinions and ideas in response to the questions posed. Nearly one in five respondents achieved the desired level of engagement by participating in a two-way dialogue about site-specific issues, making recommendations reflecting a wide diversity of opinions and viewpoints (fig. 6). In many cases, visitors commented not only on the original question posed, but also on responses submitted earlier by others. Numerous respondents indicated they enjoyed learning about park issues and hearing thoughts from their fellow hobbyists.

Quick response (QR) code use

There is considerable interest across the National Park Service in using QR codes in affiliation with exhibits, programming, and visitor center operations to quickly link people to relevant information online. As an extension to our activity, we developed online information that described park solutions to the specific problems posed at four of the five caches. Unique QR codes were used at each cache to link visitors directly to this information. We used the Google URL shortener, goo.gl, to generate all QR codes and track them over time.

A total of 667 physical visits were logged across these four caches. By comparison, all affiliated QR codes yielded a combined total of only 22 clicks, representing only 3.3% of recorded visits. The target Web pages enjoyed significantly higher visitation when accessed through the park Web site. It should be noted, however, that cellular reception is required for using QR codes. Presently, three of the cache locations receive reliable service from only one major

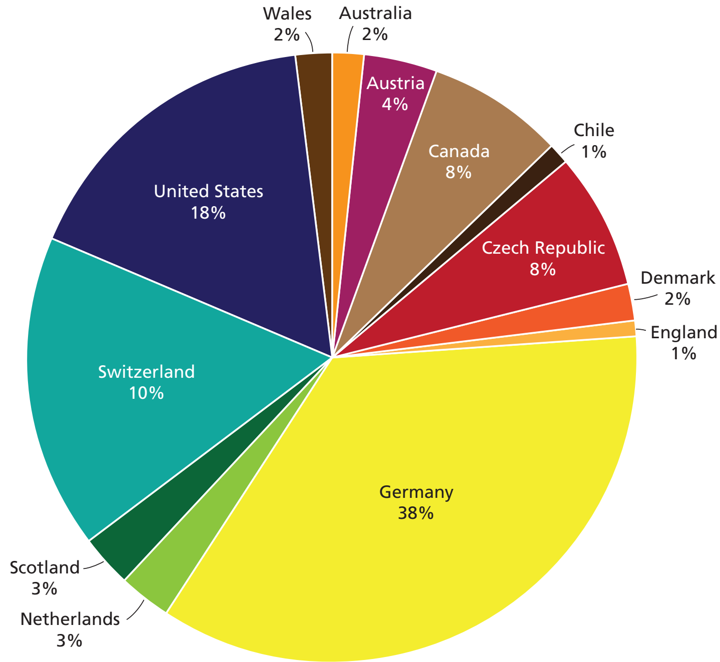

Figure 5. Percentage of use by nationality, as reported through online cache logs.

Figure 6. Injecting dialogic questions into the geocaching activity helped spur some participants beyond typical comments about the cache itself or the hunt to find it. The site bulletin for the Flamingo cache asked participants to step into the shoes of the park superintendent and decide whether to invest taxpayer money to rebuild infrastructure at the edge of a rising ocean. This word map of responses to the question posed at the Flamingo geocache helps depict the breadth of place-based discussion generated among participants.

national provider, and two of the cache sites generally have no service whatsoever. We have little doubt that usage would increase with enhanced coverage, but to what extent remains unclear.

NPS PHOTOS (2)

Figure 7. No notable impact was seen following one year of use at most sites, like Deer Hammock (above; 3 January 2013 at left, 6 February 2014 at right). However, a notable social trail did form at the Flamingo site (facing page; January 2013 at left, 6 February 2014 at right).

Site impacts from visitor use

After one year, we took repeat multiangle photographs at each cache location to document any resource impacts. Four of the five sites, including two that required some degree of vehicle access, showed no visible impacts associated with use. The Flamingo site, however, showed notable change—namely, the development of a visible social trail leading to the cache site (fig. 7).

Formation of the trail at Flamingo was not wholly unexpected, and was discussed across divisions during the planning phase of the project. Because the cache was located in a disturbed locale (the site of the old Flamingo Lodge), the potential for this impact was deemed acceptable. Also, the presence of a conspicuous and active osprey nest immediately adjacent to the cache site makes it difficult to fully attribute the social trail to geocaching. Though the social trail initially formed following placement of the cache, it has likely been maintained through the combined actions of both geocachers and birders attempting to approach the nest. There is general support for the merits of the activity at this site (Showler 2014) but modifications to this location are being discussed with Flamingo personnel and park managers.

Conclusions

Our pilot project provides compelling justification for the selective use of geocaching as an interpretive tool. Many parks are increasingly engaging audiences on controversial topics through facilitated dialogue and civic engagement. A well-designed geocaching program can be an effective, nonpersonal venue by which to provoke a diverse audience to think about, and comment on, issues of importance to them, while also considering the opinions of their peers.

The National Park Service (NPS) has generally proceeded with caution in permitting geocaching on its lands, and the activity has . . . not been widely accepted.

Roughly 20% of visitors engaged fully, responding to the management dilemma posed. The merits of this response rate can perhaps best be evaluated through comparison with other interpretive techniques. What percentage of visitors, for example, might be induced to share their viewpoints during a traditional illustrated talk or guided walk? And furthermore, what is the potential for these opinions to be considered by subsequent park visitors or park managers once shared? Here, geocaching seems to have an edge over traditional interpretive techniques, as a running record of responses provides fodder for continued discussion and consideration by activity participants and park personnel.

Our experience informs us that unwanted impacts can be minimized through proper site selection, consultation with multidisciplinary park staff, ongoing monitoring, and adaptive management. The pilot program also provides us with a useful count of average visitor use per cache log, which can now serve as a multiplier to roughly estimate future visitor use with greater ease. Last, our experience provides little optimism that QR codes provide much interpretive value because of the assumed lack of cellular service across many park areas and a general disinclination of park visitors to use them.

NPS PHOTOS (2)

Our pilot project provides compelling justification for the selective use of geocaching as an interpretive tool.

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About the authors

Larry Perez *(larry_perez@nps.gov) and* ***Rudy Beotegui*** *(rudy_beotegui@nps.gov) are with the National Park Service, Everglades National Park, 40001 State Road 9336, Homestead, FL 33034.*

PS

Tick surveillance and disease prevention on the Appalachian Trail

By Karl Ford, Robyn Nadolny, Ellen Stromdahl, and Graham Hickling

THE APPALACHIAN NATIONAL SCENIC TRAIL (AT) IS A moderate-elevation, 3,520 kilometer-mile-long (2,187 mi) hiking trail in the Appalachian Mountains extending from Georgia to Maine in the United States (fig. 1). Each year, 2–3 million people hike portions of the trail. In 2013, approximately 2,700 northbound through-hikers started out on the trail in Georgia in late winter or spring, taking five to six months to complete the hike (http://www.appalachiantrail.org/about-the-trail). During the hiking season, hikers and trail maintainers are at risk of exposure to ticks and tickborne disease agents, especially the Lyme disease bacterium *Borrelia burgdorferi*.

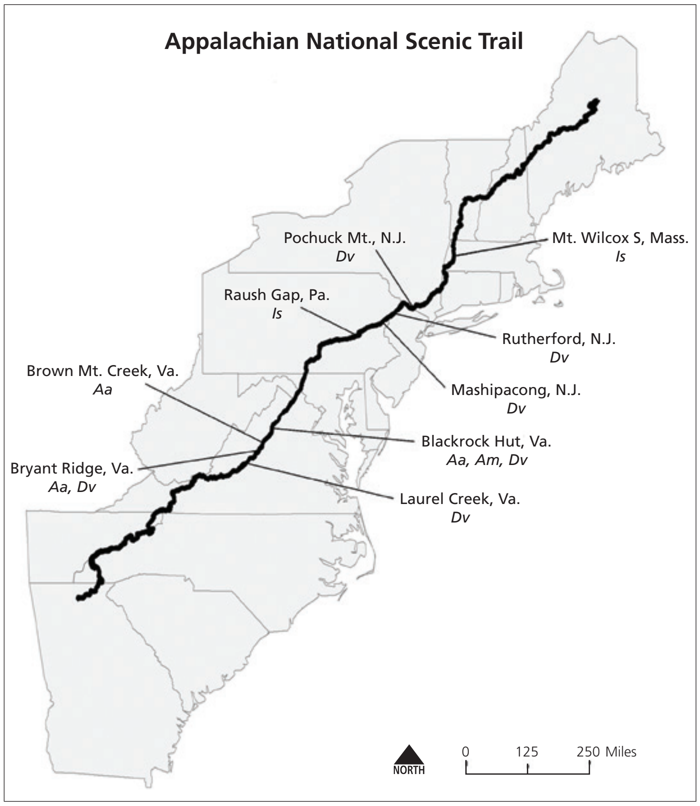

Figure 1. The Appalachian National Scenic Trail traverses parts of 14 states over 3,520 kilometers (2,187 mi) between Springer Mountain, Georgia, and Mount Katahdin, Maine. Labels indicate selected tick sampling locations.

About 33,000 cases of Lyme disease were reported in the United States in 2011, many in the New England and mid-Atlantic eastern states traversed by the AT (CDC 2013). Reported cases underestimate the true incidence, which may exceed 300,000 annually (Mead 2013). The National Park Service does not know how many cases of Lyme disease are initiated on the trail; however, 9% of respondents to an AT hiker survey reported they had been diagnosed with Lyme disease (Knoll et al. 2014). In the eastern United States, *B. burgdorferi* is transmitted to humans via the black-legged or "deer" tick, *Ixodes scapularis* (fig. 2). Juvenile (nymphal) ticks cause the most cases of Lyme disease and are about the size of a poppy seed (fig. 3). In the Northeast, most tick bites involve *I. scapularis* or the American dog tick, *Dermacentor variabilis*. In the Southeast, most bites are from the lone star tick, *Amblyomma americanum* (Stromdahl and Hickling 2012). These latter two tick species transmit ehrlichial and rickettsial diseases, but not Lyme disease.

Tick activity is highly seasonal: nymphal *I. scapularis* and adult *A. americanum* are active in spring and summer, whereas adult *I. scapularis* are active from fall through spring (Diuk-Wasser et al. 2006). In addition, ticks tend to avoid higher elevations; in a study of mid-Atlantic states, no *I. scapularis* were found above 530 m (1,739 ft) (Bunnell et al. 2003). The Centers for Disease Control and Prevention published Lyme disease case maps for the United States in 2013 that are influenced by population centers. Consequently, those maps are of limited utility in determining the likelihood of AT hikers being exposed to ticks along different sections of the trail, particularly in rural areas where population density is relatively low. Furthermore, hikers may sleep in, or camp near, primitive camping shelters on the AT. These shelters are used by rodents that are hosts for ticks and reservoirs for tickborne human pathogens.

Lyme disease risk among AT hikers

Lyme disease causes a flulike illness and, in 10–20% of treated cases and 60% of untreated cases, can result in debilitating, chronic Lyme disease syndrome. Symptoms include significant joint swelling and arthritis. A smaller percentage of cases experience neurological problems. As the manager of the Appalachian National Scenic Trail, the National Park Service supported this research to help determine Lyme disease risk to AT hikers.

Abstract

The Appalachian National Scenic Trail (AT) runs 3,520 km (2,187 mi) from northern Georgia to northern Maine, traversing 14 states where Lyme disease and other tickborne diseases are endemic or emerging. Approximately 2–3 million visitors hike the AT annually, including through-hikers who spend five to six months on the trail in spring through early fall, when common tick species are active. Disease vector tick surveillance was conducted from April through August 2013 at 42 randomly selected AT shelter areas along a south-to-north transect covering the full length of the AT. Tick abundance at shelters and tenting areas was compared with tick abundance on the AT itself, and the collected ticks were tested for common bacterial pathogens. Human-biting tick species collected comprised *Ixodes scapularis*, *Amblyomma americanum*, *Amblyomma maculatum*, and *Dermacentor variabilis*. Human pathogens *Borrelia burgdorferi* and *Rickettsia montanensis* were detected in tested ticks. Tick abundance on the trail was low overall (2.8 ticks per 1,000 m^2 sampled), but exceeded tick abundance in shelters and tenting areas by 14.5 times. No ticks were collected south of Virginia or north of Massachusetts, or above 829 m (2,720 ft) in elevation, which suggests that season and elevation are significant determinants of the risk of hiker exposure to questing ticks on the AT. Such information should be included in future health messaging to hikers along with preventive measures. Management issues are discussed.

Key words

Appalachian Trail, *Ixodes scapularis*, Lyme disease, prevention

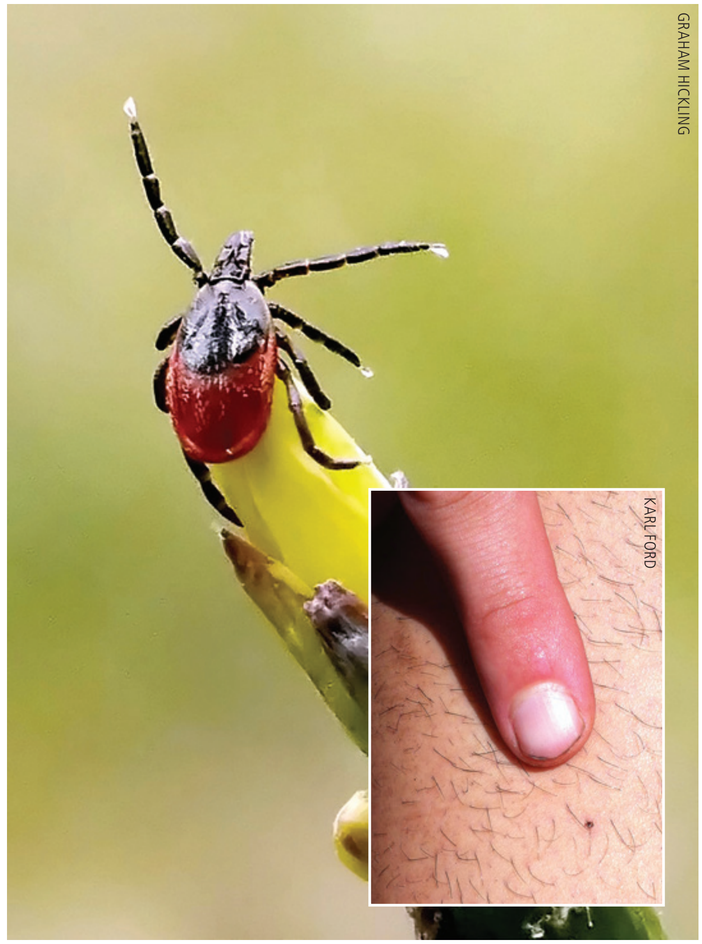

Figure 2. The black-legged or deer tick, *Ixodes scapularis*, adult shown here, is a common carrier and vector of the bacterium that causes Lyme disease in humans.

Figure 3 (inset). About the size of a poppy seed, a tick nymph embeds itself in the skin of a hiker.

Several management issues related to this public health concern drove our research on the Appalachian Trail. The first concerned the scope of the Lyme disease problem among AT users. There are no data on tick abundance around shelters and only limited data on their abundance on the trail itself (Oliver and Howard 1998). A second issue was whether or not the camping shelters might provide harborage for the reservoir of Lyme disease (mice and rodents). No data of this type were known. A final concern was to better identify tickborne disease-prevention measures, including trail vegetation trimming and hiker education. The objective of this research, therefore, was to assess species distribution and abundance of ticks at representative shelter, tenting, and trail locations that northbound through-hikers encounter on the AT.

Materials and methods

We used a stratified random sample approach to survey 42 shelter areas on a south-to-north transect along the entire Appalachian Trail (table 1, next page) in months coinciding with peak nymphal tick activity, when Lyme disease risk is considered highest (Diuk-Wasser et al. 2006). We used a 0.5 m^2 (5 ft^2) white cloth flag to sweep surfaces and vegetation to collect ticks (AFPMB 2012). At each site, we flag-swept three areas: (1) shelter floors, steps, and low walls; (2) a 1,000 m^2 (1,196 yd^2) tenting area surrounding the shelter; and (3) a 500-meter-long by half-meter-wide (1,640 ft × 1.6 ft) linear swath of trail. Collected ticks were placed in zipper-style plastic bags and shipped to the U.S. Army Public Health Command, Aberdeen Proving Ground, Maryland, for species identification and pathogen detection (using standard polymerase chain reaction [PCR] techniques described in Han et al. 2014). We tested all ticks collected for associated human pathogens.

Results

We conducted a total of 126 flagging sessions (i.e., three areas each at 42 shelters), of which 11 (8.7%) produced ticks (table 1, next page). The map shows the location of shelter areas where ticks

Table 1. Tick and pathogen collections along the Appalachian Trail, 2013

Shelter Site[1]	Date	State[2]	Elevation (m)	Tick Count: Shelter	Tick Count: Tent Camp	Tick Count: Trail	Species[3] (Number Collected)	Pathogen Status
Stover Creek	13-Apr	Ga.	875	0	0	0		
Hawk Mountain	13-Apr	Ga.	975	0	0	0		
Long Branch	20-Apr	NT	1,352	0	0	0		
Mollies Ridge	25-Apr	NT	1,393	0	0	0		
Silers Bald	26-Apr	NT	1,664	0	0	0		
Overmountain	10-May	NT	1,387	0	0	0		
Watauga Lake	13-May	NT	649	0	0	0		
Abingdon	14-May	NT	1,154	0	0	0		
Knot Maul Branch	21-May	Va.	878	0	0	0		
Pine Swamp Branch	27-May	Va.	771	0	0	0		
Laurel Creek	29-May	Va.	829	0	0	2	*Dv* (2)	0
Bryant Ridge	3-Jun	Va.	402	0	0	3	*Aa* (3)	0
Brown Mountain Creek	5-Jun	Va.	425	0	0	2	*Dv* (1), *Aa* (1)	0
Blackrock Hut	14-Jun	Va.	806	0	0	18	*Aa* (16), *Am* (1), *Dv* (1)	*Rm*-1
Crampton Gap	21-Jun	Md.	305	0	0	0		
Raven Rock	22-Jun	Md.	451	0	0	0		
Raush Gap	29-Jun	Pa.	296	0	0	1	*Is* (1)	*Bb*
Windsor Furnace	2-Jul	Pa.	268	0	0	0		
George W. Outerbridge	4-Jul	Pa.	305	0	0	0		
Kirkridge	6-Jul	Pa.	451	0	0	0		
Mashipacong	8-Jul	N.J.	434	0	1	1	*Dv* (1)	0
Rutherford	8-Jul	N.J.	410	1	0	0	*Dv* (1)	0
Pochuck Mountain	9-Jul	N.J.	256	1	1	0	*Dv* (1)	0
Fingerboard	11-Jul	N.Y.	396	0	0	0		
William Brien Memorial	12-Jul	N.Y.	326	0	0	0		
Wiley	16-Jul	N.Y.	226	0	0	0		
Limestone Spring	19-Jul	Conn.	299	0	0	0		
Riga Leanto	20-Jul	Conn.	491	0	0	0		
Mt. Wilcox S	21-Jul	Mass.	524	0	0	2	*Is* (2)	0
Mt. Wilcox N	21-Jul	Mass.	594	0	0	0		
October Mountain	22-Jul	Mass.	588	0	0	0		
Spruce Peak	27-Jul	Vt.	664	0	0	0		
Greenwall	29-Jul	Vt.	617	0	0	0		
Clarendon	30-Jul	Vt.	363	0	0	0		
Stoney Brook	31-Jul	Vt.	536	0	0	0		
Hexacuba	5-Aug	N.H.	604	0	0	0		
Ethan Pond	11-Aug	N.H.	899	0	0	0		
Rattle River	16-Aug	N.H.	384	0	0	0		
Frye Notch	17-Aug	Maine	695	0	0	0		
Bemis Mountain	19-Aug	Maine	850	0	0	0		
Sabbath Day Pond	20-Aug	Maine	728	0	0	0		
Wilson Valley	29-Aug	Maine	296	0	0	0		
All sites				**2**	**2**	**29**		**2**

[1]GPS coordinates can be found at http://web.eecs.utk.edu/~dunigan/at/.
[2]"NT" indicates the border of North Carolina and Tennessee.
[3]Species abbreviations: *Aa: Amblyomma americanum, Am: Amblyomma maculatum, Dv: Dermacentor variabilis, Is: Ixodes scapularis, Rm: Rickettsia montanensis, Bb: Borrelia burgdorferi*

Ticks were rarely found around shelters or tenting areas, and were 14.5 times more likely to be encountered on the trail itself.

were collected (see fig. 1). Despite sampling, we collected no ticks from Georgia, North Carolina, Tennessee, Maryland, New York, Connecticut, Vermont, New Hampshire, or Maine. Sampling extended from mid-April through August, but ticks were collected only from 29 May to 21 July (table 1).

One notable collection was of *A. americanum* and *A. maculatum* in western Albemarle County, Virginia, at 806 m (2,644 ft) in elevation; this is the first record of the latter species in Albemarle County. *B. burgdorferi* and *Rickettsia montanensis* (one infected tick each) were the only human pathogens detected among the 33 ticks tested.

Discussion

We conducted trail sampling in a linear swath of trail 0.5 m (1.6 ft) wide. Entomologists report tick density per 1,000 m^2. Overall tick abundance on the trail was low (2.8 ticks per 1,000 m^2 of trail), which is consistent with low densities recorded by Diuk-Wasser et al. (2006) in the Appalachian Mountains. Ticks were rarely found around shelters or tenting areas, and were 14.5 times more likely to be encountered on the trail itself. Low tick abundance is likely a consequence of the high elevation of many segments of the trail; the trail averages 760 m (2,493 ft) in elevation overall and no ticks were collected above 830 m (2,723 ft). All ticks collected came from central Virginia, Pennsylvania, New Jersey, or Massachusetts, where the trail is generally lower than the approximately 500 m (1,600 ft) limit for *I. scapularis* noted by Bunnell et al. (2003). The high elevations of the Appalachian Trail, combined with subalpine coniferous forest and alpine vegetation, constitute poor tick habitat (Jouda et al. 2004), which helps explain why no ticks were collected in Vermont, New Hampshire, or Maine despite efforts to survey these areas.

Season is an important determinant of hiker exposure to ticks. The lack of springtime collections in the southern states reflects low spring temperatures (and high elevations) of the trail, although repeat surveys in other seasons will be needed to properly quantify such patterns. The importance of the seasonally restricted sampling we report here is that it coincides with the typical timing of most hikers' and maintenance crews' use of the AT.

This survey provides only limited information on the pathogen status of the ticks, as sample sizes were small. One of three *I. scapularis* was infected with *B. burgdorferi*, which is consistent with the >20% prevalence of this pathogen typically found in nymphs in Lyme disease–endemic areas (Stromdahl and Hickling 2012). Prevalence of pathogenic *Ehrlichia* and *Rickettsia* species is low in human-biting ticks (typically <10%; Stromdahl and Hickling 2012), so it is unsurprising that only a single *Rickettsia* species was detected in our sample.

Tick prevention measures

Season, habitat type, and elevation are determinants of the risk of hiker exposure to ticks on the Appalachian Trail. This research indicates the greatest exposure to deer ticks occurs from May to July in the states of Maryland, Pennsylvania, New Jersey, New York, Connecticut, and Massachusetts, and at elevations less than around 500 meters (1,600 ft). Because of the high incidence and severity of the disease and concern for the health problems that can result, hikers should be aware of tick-prone areas, symptoms of the disease, and methods for minimizing contact with ticks. The National Park Service and other land management agencies could consider messaging as a way to provide information to prospective hikers to help make hiking safer.

The Centers for Disease Control and Prevention makes several recommendations to reduce the chance of tick bites:

- Wear factory-treated permethrin clothing and treat shoes, pack, and outer tent floor with spray-on 0.5% permethrin (http://www.cdc.gov/lyme/prev/on_people.html). Permethrin binds to clothing, is safe for humans, and is highly repellent of ticks, spiders, and insects (http://www.epa.gov/pesticides/factsheets/factory-treated-clothing.html). We recommend treated ventilating bug-net pants, long-sleeved shirt, and hat.

Low tick abundance is likely a consequence of the high elevation of many segments of the trail.

The importance of the seasonally restricted sampling we report here is that it coincides with the typical timing of most hikers' and maintenance crews' use of the AT.

KARL FORD

Figure 4. Hikers and volunteer trail maintainers alike are at risk of exposure to ticks and tickborne disease agents.

Proper clothing treated with permethrin is the single most important preventive measure a hiker can take.

- Apply 20–30% DEET repellent on exposed skin, but use it sparingly and according to directions on adults and children because DEET is toxic. Higher concentrations are unnecessary. Alternatively, wear a net to protect your head and face.
- Conduct a daily (or more frequent) tick check. Look for adult or juvenile (nymph) ticks (see fig. 3). Enlist a hiking buddy to check your back. Perform a partial check of body and clothing during breaks and after collecting firewood and do a more complete check at the end of the day.
- Shower or bathe as soon as possible after leaving the trail and conduct a full-body tick check. Put clothing in a dryer for an hour to kill any ticks present.
- Be able to identify deer ticks and recognize the symptoms of Lyme disease (http://www.cdc.gov/lyme/ or http://www.lymediseaseassociation.org).
- Immediately remove any attached tick with forceps with a slow, steady pull. Wash the bite area carefully with soap and water or sanitizer.
- Seek medical treatment immediately if any flulike symptoms occur and be aware that an expanding rash may or may not be present.

The lead author hiked the entire trail and has several additional recommendations for avoiding contact with ticks:

- Hike the center of the trail and use caution hiking off-trail, such as when collecting firewood. Tick exposure is reduced by regular trail, field, power line, and shelter area vegetation trimming (fig. 4).
- Avoid sitting on the ground or on logs and refrain from setting your pack or gear on the ground, if possible. Treat a closed-cell sit pad with permethrin for rest breaks.
- Avoid pitching your tent in leaf piles or grass. Tents may be safer than tarps. Bare ground is safer than areas covered with leaf litter or grass and is in accordance with Leave-No-Trace principles. Shelters and picnic tables are fairly safe places, but examine them first.
- Avoid hiking and camping with dogs, as dogs attract ticks. Close contact, as in petting or sleeping, may enable the ticks to bite humans.

Further research

Although this work was the first study of tick abundance encompassing the entire AT, it is limited to the dates and locations sampled. Additional trailside sampling is needed in the southern states and in Maine from May to July. In addition, more intensive trailside sampling from northern Virginia through Connecticut could better identify high-risk areas. Modeling and observational data suggest *I. scapularis* is extending its range because of climate change (Ogden et al. 2014).

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About the authors

***Karl Ford** is an environmental scientist and natural resource specialist, retired from the Bureau of Land Management. He lives in Golden, Colorado, and can be reached at earthford@aol.com. **Robyn Nadolny** is a PhD candidate in ecological sciences in the Department of Biological Sciences, Old Dominion University, Norfolk, Virginia. **Ellen Stromdahl** is an entomologist with the U.S. Army Public Health Command, Aberdeen Proving Ground, Maryland. **Graham Hickling** is a research associate professor and director of the Center for Wildlife Health, Department of Forestry, Wildlife and Fisheries, University of Tennessee in Knoxville.*

Parks, pikas, and physiological stress: Implications for long-term monitoring of an NPS climate-sensitive sentinel species

By Jennifer L. Wilkening and Chris Ray

AMERICAN PIKAS (*OCHOTONA PRINCEPS*) ARE charismatic inhabitants of mountainous and rocky areas in many national parks of the western United States (fig. 1). These cold-adapted members of the rabbit order, commonly known as rock rabbits, are sensitive to warmer temperatures and rely on access to cooler microclimates located underneath rocky habitats, such as talus (Hafner 1993). As a result of recent climate-mediated population declines and extirpations, pikas have become widely considered a sentinel species for detecting ecological effects of climate change (Beever et al. 2011). Projections suggest that populations will continue to decline (Ray et al. 2012), and the species has been considered for listing as threatened or endangered at the state and federal levels. Interest in documenting changes in pika distribution is growing; in response the National Park Service (NPS) recently funded a research program, called Pikas in Peril (PIP), designed to assess vulnerability of pikas in national parks to future climate scenarios.

Figure 1. American pika (*Ochotona princeps*) in Rocky Mountain National Park, Colorado.

The PIP program is a collaborative research effort among multiple university researchers and park staff from eight western national parks (fig. 2). The main goals of the program are to document pika occurrence patterns and distribution, measure gene flow and connectivity of populations, and predict impacts of future climate change on pika populations (Garrett et al. 2011). Occupancy surveys were conducted in eight western parks in 2010 and 2011. Survey crews recorded evidence of pika presence or absence at dozens of plots within each park each year, and also evaluated pika habitat and collected fresh fecal pellets for DNA analysis. Pikas are ideal candidates for occupancy surveys because their presence is easy to detect. Data generated from these studies are being used to relate pika occupancy to habitat characteristics (Jeffress et al. 2013), which will allow park managers to identify prime habitat and predict the future distribution of the species under climate-change scenarios (Garrett et al. 2011).

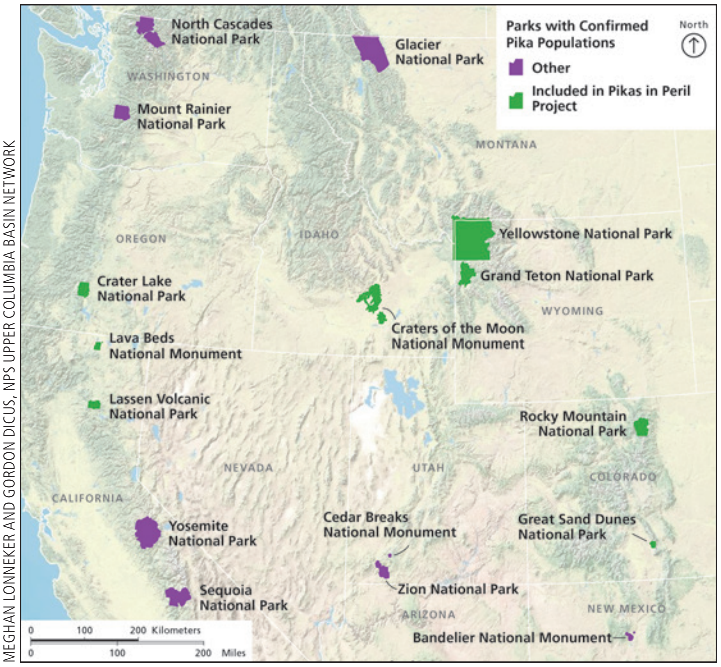
However, patterns of pika presence and absence such as used in the PIP study may be confounded by transient processes and source-sink dynamics. For example, pika populations tend to be small because habitat patches are small and pika territories are largely nonoverlapping (Smith and Weston 1990). These small populations may experience temporary extirpation because of a sequence of random and unrelated deaths (demographic stochasticity) or a rare event (environmental stochasticity). These stochastic extinctions can occur in otherwise suitable habitats (Morrison and Hik 2007), obscuring the relationship between habitat quality and pika presence. Extinctions caused by poor habitat quality can also create a bias in occupancy data if the species easily recolonizes poor-quality “sink” patches through dispersal from high-quality “source” patches. Such source-sink dynamics can make a poor-quality habitat appear suitable, while stochastic extinctions make suitable habitats appear unsuitable. To supplement presence-absence data and to predict trends in occupancy that may not yet be apparent, it would be useful to have data on the physiological response of pikas to their local habitats.

Abstract

American pikas are widely considered a sentinel species for detecting ecological effects of climate change. They are declining within a large portion of their range, and the National Park Service (NPS) recently initiated a research program, Pikas in Peril (PIP), which is designed to assess pika vulnerability to predicted changes in climate. As part of the PIP program, we collected fresh fecal samples from eight western national parks. We also tested fecal sample storage techniques using feces collected from pikas that were live-trapped, thus validating storage protocols established by NPS surveyors. Finally we measured physiological stress (glucocorticoid metabolites, GCM) in pikas in parks using fecal samples collected non-invasively. Here we present baseline values of GCM concentration for pikas across the western United States, which can be used to identify changes in physiological stress levels for this climate-sensitive species. Our research contributes to the understanding of climate change effects on this sentinel mammal, and provides park managers with baseline information that can be incorporated into long-term monitoring studies.

Key words

American pikas, climate change, non-invasive sample collection, Pikas in Peril program, stress physiology



MEGHAN LONNEKER AND GORDON DICUS, NPS UPPER COLUMBIA BASIN NETWORK

Figure 2. Location of the eight national parks across the western United States being studied as part of the Pikas in Peril program.

One method for identifying potential stressors directly affecting individuals is to measure physiological stress. Stress hormone metabolites found in fecal samples are used increasingly to evaluate stress in sensitive populations of birds and mammals. In response to a stressor, animals release glucocorticoid hormones (such as cortisol or corticosterone) into the bloodstream. These hormones circulating in the body are metabolized by the liver and then excreted as metabolites into the gut. Glucocorticoid metabolites (GCMs) can be detected in the excrement of birds and mammals (Möstl and Palme 2002).

Fecal samples can be collected relatively easily and non-invasively, important considerations for a species in decline such as pikas. Of course, animals must be handled to validate the use of GCMs as a metric of stress, but non-invasive sampling is possible following validation. Validation should address not only the relationship between stress and GCM in samples collected non-invasively, but also the potential influence of environmental factors acting directly on GCM concentration in those samples after deposition. Environmental conditions such as temperature or humidity can alter microbial activity, which can result in increased decomposition of steroid metabolites and biased measurements of metabolite concentration (Millspaugh and Washburn 2004). Therefore, accurately comparing GCM concentrations from samples collected across the western United States may be difficult, since environmental conditions can vary considerably in different regions. Similarly, sample storage techniques have been found to alter GCM concentration in fecal samples (Khan et al. 2002), and must be tested to interpret results reliably.

Here we present a practical application of recently developed techniques for non-invasively measuring stress in pikas, using fresh fecal samples that were collected as part of the PIP program. In this study, our first objective was to examine the effects of storage methods on stress hormone metabolite concentration (GCM) in pika fecal pellets. By comparing GCM concentration measured in control samples with that in samples that were placed in storage envelopes for varying amounts of time, we tested whether storage methods directly alter GCM concentrations measured in samples. Our second objective was to non-invasively measure physiological stress (GCM concentration) in pikas living in national parks throughout the western United States. We present baseline values of GCM concentration for pikas in eight national parks, which can be used to identify future changes in physiological stress levels for this climate-sensitive species. Finally, we provide additional information regarding how our established techniques can contribute to long-term monitoring and management programs related to pikas and other NPS key vital signs.

Methods

Testing effects of sample storage (objective 1)

To obtain fecal samples, we took advantage of an ongoing demographic study of pikas at the Niwot Ridge Long-Term Ecological Research Site in Colorado. Fresh fecal pellets were collected from live-trapped, anesthetized pikas as a by-product of determining each animal's sex, because manipulations required to observe the genitals often result in fecal pellet excretion. Additional pellets were often collected from inside the trap or anesthetizing chamber, or from the rock that had supported the (wire-mesh) trap. Samples were collected from individuals that had been in traps for less than 3 hours, which ensured that measured GCM concentration represented a baseline level (GCM increase in response to stress does not occur until 10–15 hours after initiation of a stress-inducing event, such as trapping) (Wilkening et al. 2013). Trapping and sampling procedures were reviewed and authorized by Colorado Parks and Wildlife (license TR2014), and procedures followed those approved by the University of Colorado–Boulder Institutional Animal Care and Use Committee (protocol 1104.06). Fecal pellets used for this study were from adult female pikas, to control for observed differences in GCM concentration resulting from gender and age, and each female was released where captured within 15 minutes after sampling. Fecal samples were placed into storage tubes, kept on ice in the field, and transferred within 12 hours to a −20°C (−4°F) freezer. Pellets collected from six individuals were pooled and divided at random into 14 samples: two controls and 12 samples slated for experiment. Each sample consisted of approximately nine pellets, for an average of 21 pellets per pika, placed inside a small paper envelope (coin envelope). Envelopes were kept at room temperature in a dry location, and storage methods mimicked those already in use by NPS staff and trained project volunteers (Jeffress and Garrett 2011). Each envelope was stored for a different number of months (1–12), and envelopes were numbered according to storage time (for example, envelope 1 = one month, 2 = two months). After each specified time period, samples were removed from envelopes and placed in storage vials in a −20°C freezer. Control samples were maintained in a −20°C freezer during the entire period and GCM analysis was performed on all samples at the same time.

We extracted GCM using protocols previously validated for pikas (Wilkening et al. 2013). Comparative analysis of GCM concentration in samples was conducted using a commercially available Corticosterone Enzyme Immunoassay Kit (Arbor Assay Design, Inc., Ann Arbor, MI; catalog number K014-H1). Final concentrations of fecal GCM were expressed as ng GCM/g (or parts per billion, ppb) dry feces. GCMs were extracted using all pellets from each envelope, and extractions from each envelope were assayed in duplicate. We used duplicate extractions to calculate the mean

Figure 3. Pika scat is adhered to a rock with urine; scat identified as fresh (deposited within the past month) is based upon its position in the pile as well as its color and consistency.

GCM concentration for each sample, and related these means to sample storage times using a linear regression analysis. Linear regression assumes a straight-line relationship between the response variable (GCM concentration) and the predictor variable (storage time), and requires that the residuals (error or scatter of data points around the regression line) be normally distributed with no trend or autocorrelation related to the predictor variable. We examined residuals, residual autocorrelation, and a normal probability plot to confirm the validity of these assumptions. We assumed there was a significant linear relationship between GCM concentration and storage time if the probability of no relationship between these variables was less than 0.05. All statistical analyses were conducted using R 3.0.1 statistical software (R Core Team 2013).

Comparing pika stress hormone levels among parks (objective 2)

Survey crews collected fresh scat samples from pika-occupied habitats in each of eight National Park System units included in the PIP research program: Crater Lake National Park, Oregon; Craters of the Moon National Monument and Preserve, Idaho; Grand Teton National Park, Wyoming; Great Sand Dunes National Park and Preserve and Rocky Mountain National Park in Colorado; Lassen Volcanic National Park and Lava Beds National Monument in California; and Yellowstone National Park in Montana, Idaho, and Wyoming (see fig. 2). Habitats within these parks represent a broad range of those preferred by American pikas, including high-elevation talus slopes and boulder fields and

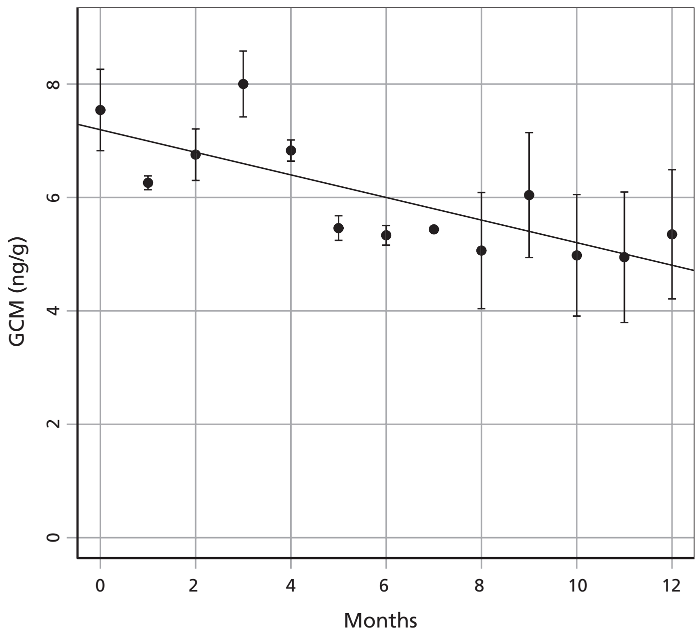


Figure 4. Mean and standard error of GCM concentration measured in samples stored unfrozen for different numbers of months. GCM concentration is expressed in nanograms/gram (parts per billion) of feces sampled. Sample number corresponds to the number of months samples were kept in storage envelopes, and 0 months represents control groups. The whiskers show standard error among samples assayed in duplicate.

Stress hormone metabolites found in fecal samples are used increasingly to evaluate stress in sensitive populations of birds and mammals. . . . Glucocorticoid metabolites (GCMs) can be detected in the excrement of birds and mammals.

lower-elevation lava flows underlain by ice features. Permits for fecal pellet sampling were obtained for each park in each year of the study, as directed in the PIP protocol (Garrett et al. 2011). Surveyors collected samples within and en route to sites randomly selected for pika occupancy surveys during 2010 and 2011. Collection protocols followed those established by Jeffress and Garrett (2011), and fresh fecal pellets were collected only from currently occupied pika territories as evidenced by a fresh hay pile or active latrine. Pikas maintain established latrines within territories and fecal pellets can be identified as fresh by color, consistency, and relative positioning (fig. 3). Surveyors in all parks attended group trainings that described collection and storage protocols, and were also given detailed field manuals for reference. Fecal pellets were transferred into coin envelopes using twigs or similar devices to avoid human contamination. Each envelope contained 8–14 pellets, and GCM concentrations were determined from 8 to 35 envelopes per park. Envelopes were labeled with the collection date, time, and location (GPS coordinates) and sealed with tape or stickers. To ensure that each sample represented an individual pika, we did not analyze samples that were collected within 50 meters (164 ft) of each other. We took care to prevent pellets from being crushed, and kept collection envelopes in a cardboard box or similar receptacle. Samples were kept at room temperature in a dry environment and later mailed to the University of Colorado in Boulder, where GCM extraction and comparison procedures followed those detailed above. One-way ANOVA (analysis of variance) was used to test for differences between GCM concentrations (adjusted for storage time) among parks.

Results

Testing effects of sample storage (objective 1)

Concentration of GCM was strongly affected by storage conditions. GCM concentration fell 4% per month and 33% per year on average in samples stored dry at ambient temperatures, relative to controls stored at −20°C (fig. 4). These results indicate that samples should be stored in the freezer immediately following collection; alternatively, the expected reduction in detectable GCM should be accounted for. In our experiment, there was a linear reduction in GCM concentration y, with the number of months, m, that a sample was stored unfrozen ($y = 7.19 - 0.20m$, $p < 0.001$, adjusted $r^2 = 0.56$). We used this relationship to estimate the pre-storage GCM concentration in each sample, given the number of months the sample was stored unfrozen.

Comparing pika stress hormone levels among parks (objective 2)

Using either observed or adjusted estimates, we found considerable variation in GCM concentration among parks (fig. 5). In the observed data, mean GCM concentration was lowest at Rocky Mountain (7.13 ng/g = nanograms of GCM per gram of feces or 7.13 ppb) and highest at Lava Beds (19.3 ng/g or ppb). There was also less variation in GCM measurements at Lava Beds, with most values being in the higher range (17.4–21.2 ng/g or ppb, table 1). In contrast, the range of GCM values recorded at several other parks was large, such as at Craters of the Moon (7.7–28.8 ng/g or ppb) and Rocky Mountain (2.8–21.2 ng/g or ppb, table 1). The pattern of relative GCM concentration among parks was similar in data observed and adjusted for time in unfrozen storage, but adjusted concentrations averaged 4 units higher than observed (mean concentrations were 9.87 and 13.86 ng/g or ppb in observed and adjusted data, respectively). ANOVA results showed a highly significant effect of park on adjusted GCM ($F [7, 80] = 9.28$, p-value < 0.001), indicating that adjusted GCM concentration differed significantly among parks.

Discussion and management implications

Fecal samples differed among parks in a common metric of stress, fecal GCM. Exposure to uncontrolled ambient conditions during storage affected observed GCM concentration, but there was a strong linear relationship between GCM concentration and storage time. This relationship was used here in a preliminary attempt to adjust for storage time and estimate GCM concentration prior to storage. In some cases these estimates involved extrapolation beyond the range of the observed relationship between GCM and storage time, requiring caution in the interpretation of results. Further experiments will be necessary to determine whether the linear relationship observed here extends to situations where initial GCM concentrations are higher and storage times longer than in the current experiment. Given this caveat, alternatives to estimation may be preferred. Exposure to uncontrolled ambient conditions could be avoided if samples were collected fresh and immediately stored frozen. This could be accomplished if pika latrines were located, cleaned of accumulated pellets, and revisited for sampling within a few days.

Observed and adjusted estimates of GCM concentration resulted in similar ranking of parks in terms of the degree and range of putative pika stress. We propose several hypotheses that could explain variation in GCM concentration observed both within and among parks. First, the range of GCM values measured in each park includes samples collected from adult male and female

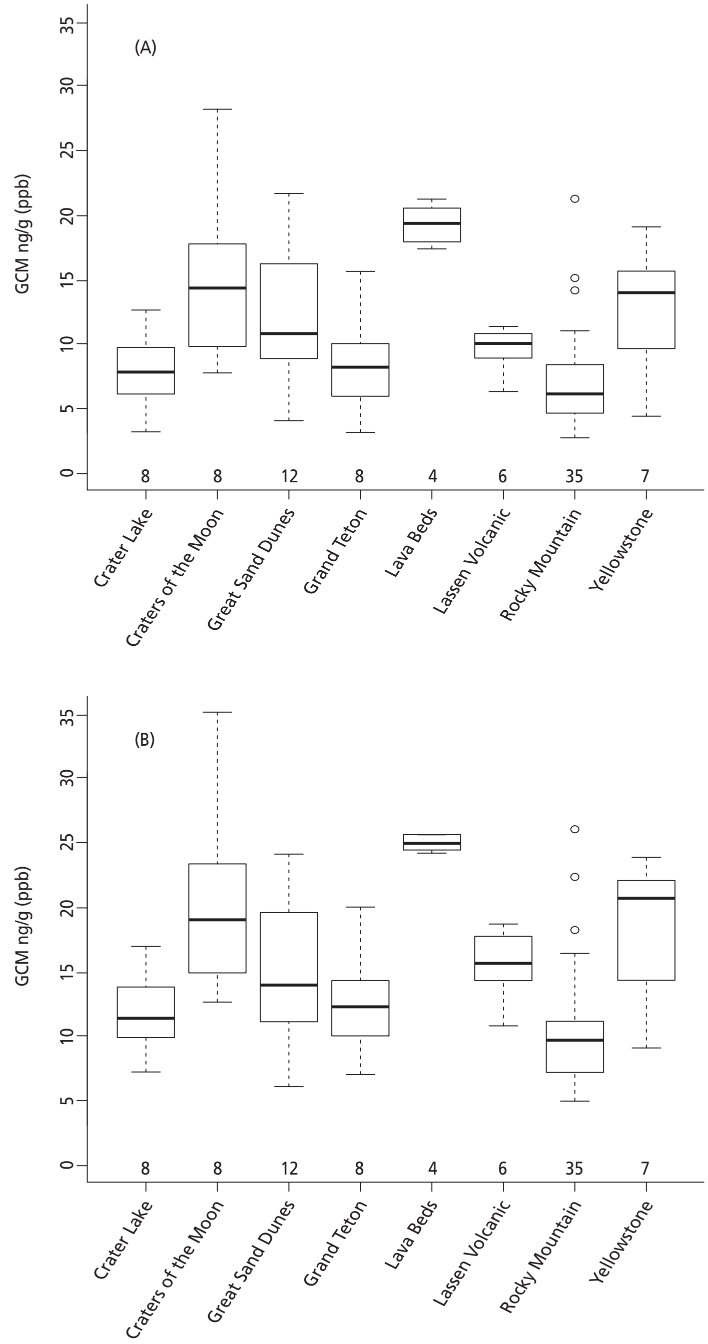


Figure 5. GCM concentration observed at the time of analysis (top) and adjusted for storage time (bottom) in samples collected from National Park System units from 2010 to 2011. Boxes depict medians and 25% and 75% quartiles. Whiskers extend through the 95% interquartile range. GCM concentration is expressed in nanograms/gram or ppb. Adjusted data (B) account for the number of months each sample was stored unfrozen using our empirical relationship $y = b + 0.20m$, where y is observed GCM concentration, m is number of months stored unfrozen, and b is initial GCM concentration. Adjusting for storage time did not alter the relative levels of this stress metric among parks.

Table 1. Comparison of stress hormone metabolite concentration adjusted for storage time (adjusted GCM) and environmental characteristics at eight western national parks

Park	Adjusted GCM ng/g (ppb)	Elevation m*	Elevation ft	Precipitation cm*	Precipitation in
Crater Lake National Park	11.8 (± 1.1)	2,115 (1,701–2,530)	6,939 (5,581–8,268)	156.7 (104.5–183.1)	61.7 (41.1–72.1)
Craters of the Moon National Monument and Preserve	20.3 (± 2.6)	1,700 (1,511–1,833)	5,577 (4,957–6,014)	32.7 (23.1–37.4)	12.9 (9.1–14.7)
Grand Teton National Park	12.5 (± 1.4)	2,815 (2,090–3,635)	9,236 (6,857–11,926)	171.9 (95.9–235.5)	67.7 (37.8–92.7)
Great Sand Dunes National Park and Preserve	15.1 (± 1.6)	3,427 (2,647–3,987)	11,243 (8,684–13,081)	86.2 (38.9–104.1)	33.9 (15.3–41.0)
Lassen Volcanic National Park	15.5 (± 1.1)	2,282 (1,731–3,089)	7,487 (5,679–10,135)	218.0 (85.0–308.4)	85.8 (33.5–121.4)
Lava Beds National Monument	25.0 (± 0.3)	1,463 (1,249–1,717)	4,800 (4,098–5,633)	43.3 (31.2–58.0)	17.0 (12.3–22.9)
Rocky Mountain National Park	10.4 (± 0.8)	3,462 (2,572–3,795)	11,358 (8,438–12,451)	98.4 (45.2–130.8)	38.7 (17.8–51.5)
Yellowstone National Park	18.1 (± 2.1)	2,424 (1,651–3,088)	7,953 (5,417–10,131)	94.5 (33.2–140.4)	37.2 (13.1–55.3)

*Data from Jeffress et al. 2013.

Notes: Means are given, followed by the standard error (for GCM concentration) or the range of values (for elevation and precipitation) measured from each park. Annual precipitation data were obtained from the PRISM Web site (www.prism.oregonstate.edu), which provides grid-based estimates at 800-meter resolution for years 1971–2000 using parameter-elevation regressions on independent slope models.

pikas. Concentration of GCM has been shown to vary considerably between the sexes, with measurements in samples collected from males being almost twice as high (Wilkening et al. 2013). If sample sizes are small and collection localities do not encompass large geographic areas, GCM values within an area could reflect only males or females, leading to skewed larger or smaller overall GCM concentrations. Second, temperature and precipitation or humidity regimes are not the same across different parks, and these factors can influence GCM concentration in samples collected non-invasively. Differing environmental factors (such as increased temperature or precipitation) can alter GCM concentration in feces, which can occur when samples are not collected in the same ecoregion and same season. For example, table 1 displays the large range of precipitation and elevation values measured in each park. Elevation is often considered a proxy variable for temperature, with lower-elevation areas correlating with higher temperatures. Average GCM concentration is highest in parks with lower-elevation habitat (Craters of the Moon and Lava Beds, table 1), indicating that high temperatures may be increasing GCM concentration in exposed samples, or pikas subject to higher temperatures may be experiencing higher stress. Diet can alter GCM concentration, since hormones pass through the digestive system (Touma and Palme 2005). Pikas are generalist herbivores and feed primarily on locally abundant vegetation, which varies by region and among parks. Other factors that may vary among parks and contribute to higher levels of pika stress include predation pressure and human disturbance impacts (such as proximity to roads or trails). Additional analyses investigating the influence of habitat characteristics specific to each park may help to explain the variation we observed.

This is the first study to present multiregional values of a physiological stress metric measured in pikas, an important indicator species occurring in a large number of western parks. Additionally, the spatial extent of our research is unique, since there are no other studies measuring physiological stress in a species across such a large and varied geographic area. Samples collected non-invasively should represent baseline values of GCM concentration in each park. Previous research has shown that exposure to environmental conditions does not influence GCM concentration if samples are collected within a single ecoregion during the same season (Wilkening et al. 2015). Pika fecal samples are typically collected during the summer months (because of weather constraints), and ecoregions do not vary within parks. Thus, park managers can use baseline values given here (based on our adjusted estimates) to document any changes in this stress metric over time measured in a particular park. Results from our study add a vital physiological component to methods of estimating population vulnerability, helping to improve our understanding of the potential for effects of climate change on this species.

This is the first study to present multiregional values of a physiological stress metric measured in pikas, an important indicator species occurring in a large number of western parks.

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About the authors

Jennifer L. Wilkening *(Jennifer.Wilkening@colorado.edu) is a former recipient of an NPS George Melendez Wright Climate Change Fellowship, and conducted this research while a PhD student at the University of Colorado, Boulder.* ***Chris Ray*** *is a research associate at the University of Colorado, Boulder.*

PS

Survey of an endangered bat roost at Coronado National Memorial, Arizona

By Amanda Best, Gabrielle Diamond, Joel Diamond, Debbie Buecher, Ronnie Sidner, David Cerasale, and James Tress Jr.

With contributions from Linda Dansby, Jason Mateljak, Adam Springer, Mike Wrigley, and Tim Tibbitts

Abstract

To protect a lesser long-nosed bat post-maternity roost, the National Park Service installed bat-compatible gates on the entrances to the abandoned State of Texas Mine within Coronado National Memorial in southeastern Arizona. Video camcorder surveys performed during peak occupation of this roost examined colony size, gate-induced injury or mortality, and bat exit rates. Although the colony decreased in size after the installation of the gate, the reduced number of bats cannot with certainty be attributed to the presence of the gate. A large wildfire and drought likely contributed to reduced numbers. The study did not find evidence that the gates caused injury or mortality, or impeded the bats while exiting the roost. Further monitoring could ensure that lesser long-nosed bats continue to use the State of Texas Mine.

Key words

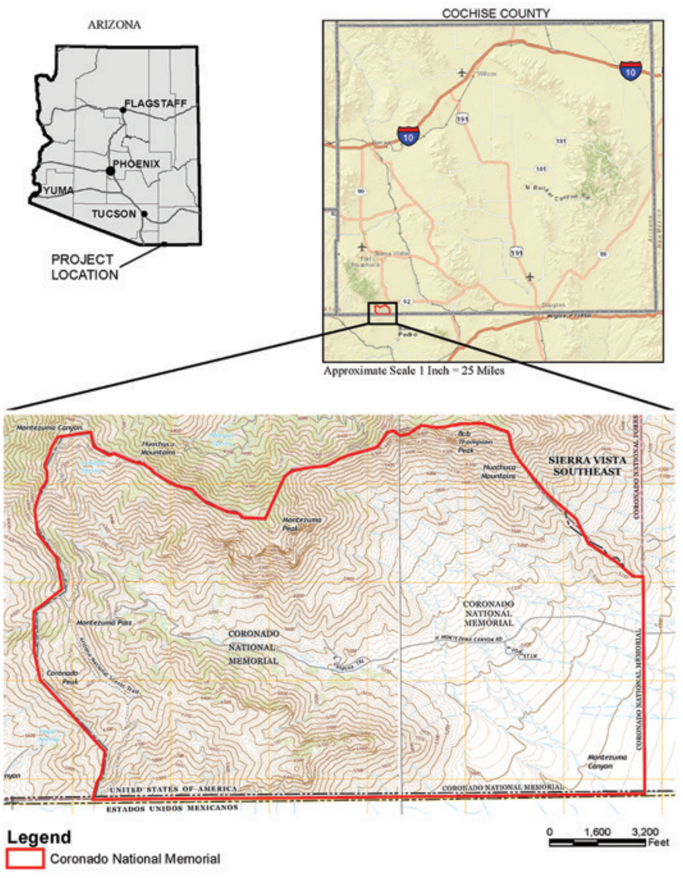
Arizona Game and Fish Department, bat-compatible gates, bat emergence rates, bat migration, bat roosts, Coronado National Memorial, endangered bats, endangered species, Huachuca Mountains, *Leptonycteris yerbabuenae*, lesser long-nosed bats, State of Texas Mine, U.S. Fish and Wildlife Service, video camcorder survey

CORONADO NATIONAL MEMORIAL IS WITHIN THE Huachuca Mountains in southeastern Arizona on the U.S.-Mexico border (fig. 1, next page). There are numerous abandoned mines within the memorial, including adits and shafts that are used by bats as roosting sites. One such abandoned mine is the State of Texas Mine, which was active from 1897 until 1947 producing primarily copper but also some zinc, lead, silver, and gold (Mindat.org and the Hudson Institute of Mineralogy 2015). The mine is used as a roost from July to October by lesser long-nosed bats (*Leptonycteris curasoae yerbabuenae*) (fig. 2, next page). This bat species is migratory (between Central Mexico and southern Arizona) and nectarivorous (feeds on nectar), and was listed as endangered by the U.S. Fish and Wildlife Service (USFWS) in 1988 (53 FR 38456).

Lesser long-nosed bats travel approximately 1,500 miles (2,414 km) yearly to reproduce in maternity colonies in northern Mexico and southwestern Arizona (Ceballos et al. 1997; Rojas-Martinez et al. 1999). These bats feed on plants within the families Cactaceae and Agavaceae (Cockrum and Petryszyn 1991; Fleming et al. 1998; Stoner et al. 2003) and follow seasonal flowering and fruiting patterns (Wilkinson and Fleming 1996; Ceballos et al. 1997; Rojas-Martinez et al. 1999). As a consequence of this tie to seasonal flowering cycles, lesser long-nosed bats typically arrive in northern Mexico and southwestern Arizona in early summer (Ceballos et al. 1997; Rojas-Martinez et al. 1999). During the early part of their stay in Arizona (late April to late July), pregnant females congregate at traditional roost sites, give birth, and raise their young at lower elevations within the range of columnar cacti. By late July, most females and young have dispersed from the maternity colonies and some have moved to higher elevations in southern Arizona, shifting their diet to the nectar of flowering paniculate agaves (those with loose, irregular flower clusters), including Palmer's agave (*Agave palmeri*) (fig. 3, next page). During late summer these bats roost at post-maternity sites like the State of Texas Mine.

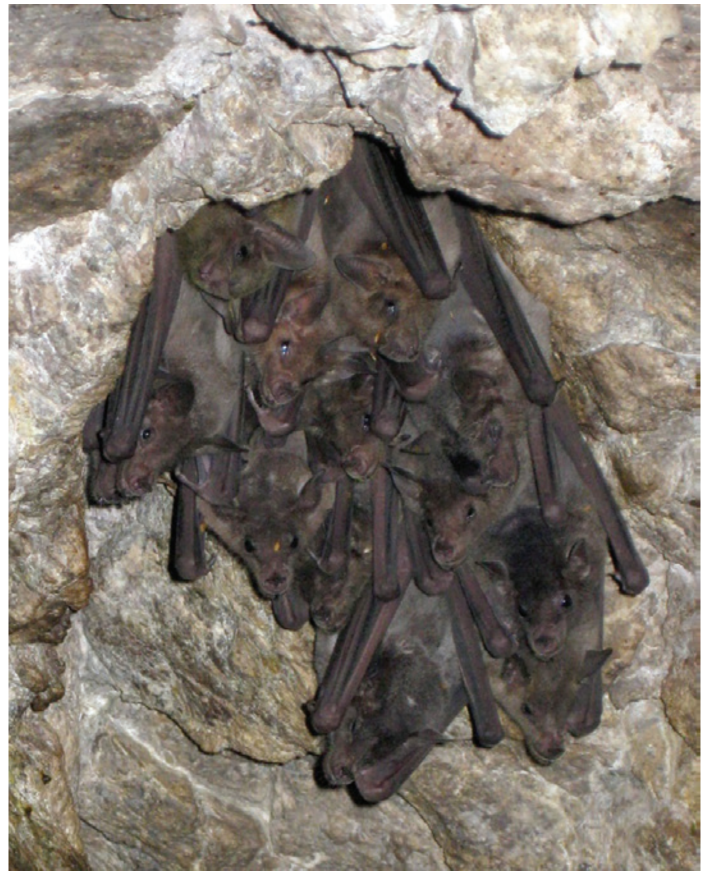
Lesser long-nosed bats were first detected roosting in the State of Texas Mine in 1993, five years after the mine's entrances had been secured with aircraft cable nets to prevent people from entering. Unfortunately, the cable nets at the State of Texas Mine were easily breached. Lesser long-nosed bats are highly susceptible to roost disturbance by humans, and high human activity generally leads to the complete abandonment of roosts. Coronado National Memorial has a high volume of illegal immigration and drug trafficking because of its proximity to the U.S.-Mexico border; areas historically used by these migrants and traffickers include the State of Texas Mine. Thus, it became necessary to protect the public and this bat roost with a more robust closure.

In order to protect lesser long-nosed bats roosting in the State of Texas Mine, the National Park Service closed all three entrances to the roost with bat-compatible steel gates (fig. 4, page 51). The three entrances include the main portal (fig. 4A, page 51), equipped with a large custom-fit cupola in 2010; a smaller side opening just west of the main portal that was equipped with a steel cupola in 1997 (at left in fig. 4B); and a lower opening just southeast of the main portal equipped with a standard bat gate in 2010 (fig. 4C, page 51). While these gates mitigated the threat of human disturbance to roosting lesser long-nosed bats and used bat-accessible designs, their impact on bat behavior and overall colony size needed to be evaluated.



COCHISE COUNTY MAP: T24S, R20E, PORTION OF SECTION 13; USGS 7.5' QUADRANGLE: MONTEZUMA PASS

Figure 1. Location of Coronado National Memorial and the State of Texas Mine, site of the 2010–2013 bat gate surveys.

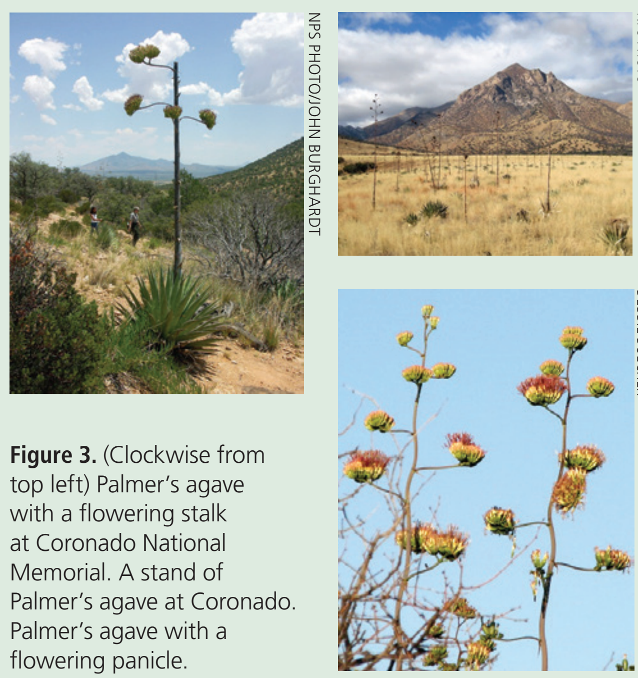


GABRIELLE DIAMOND

Figure 2. Lesser long-nosed bats roost in an alcove of the State of Texas Mine lower adit in 2010.

Study objectives

Coronado National Memorial consulted with the U.S. Fish and Wildlife Service prior to construction of the main cupola at the State of Texas Mine regarding potential impacts on the endangered bats. The National Park Service contracted Westland Resources, Inc., and the Arizona Game and Fish Department Wildlife Contracts Branch to design a study to monitor the bats' use of the State of Texas Mine. The study would examine colony size, gate-induced injury or mortality, and bat exit rates. Surveys to quantify emergence counts and exit rates were conducted at the mine from 2010 to 2013 to assist the National Park Service and the U.S. Fish and Wildlife Service in determining how the bats' use of the newly constructed cupola compared with their use of the cable net closure. The cable net closure condition is this study's baseline condition as determined by the USFWS (2010), meaning it is the basis for determining the potential impacts of the newly constructed cupola.



NPS PHOTO/JOHN BURGHARDT

NPS PHOTO

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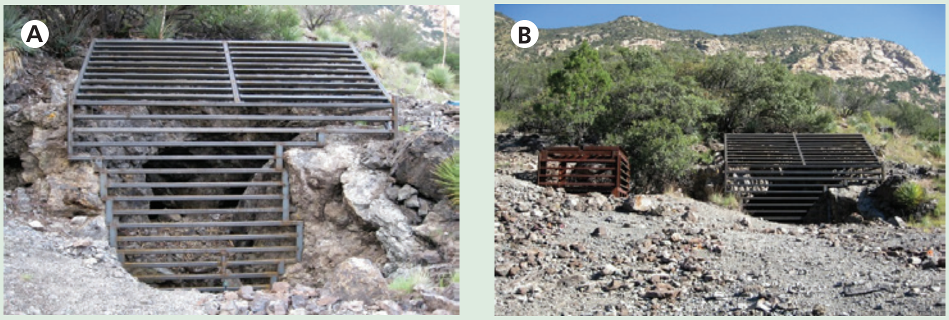
Figure 3. (Clockwise from top left) Palmer's agave with a flowering stalk at Coronado National Memorial. A stand of Palmer's agave at Coronado. Palmer's agave with a flowering panicle.



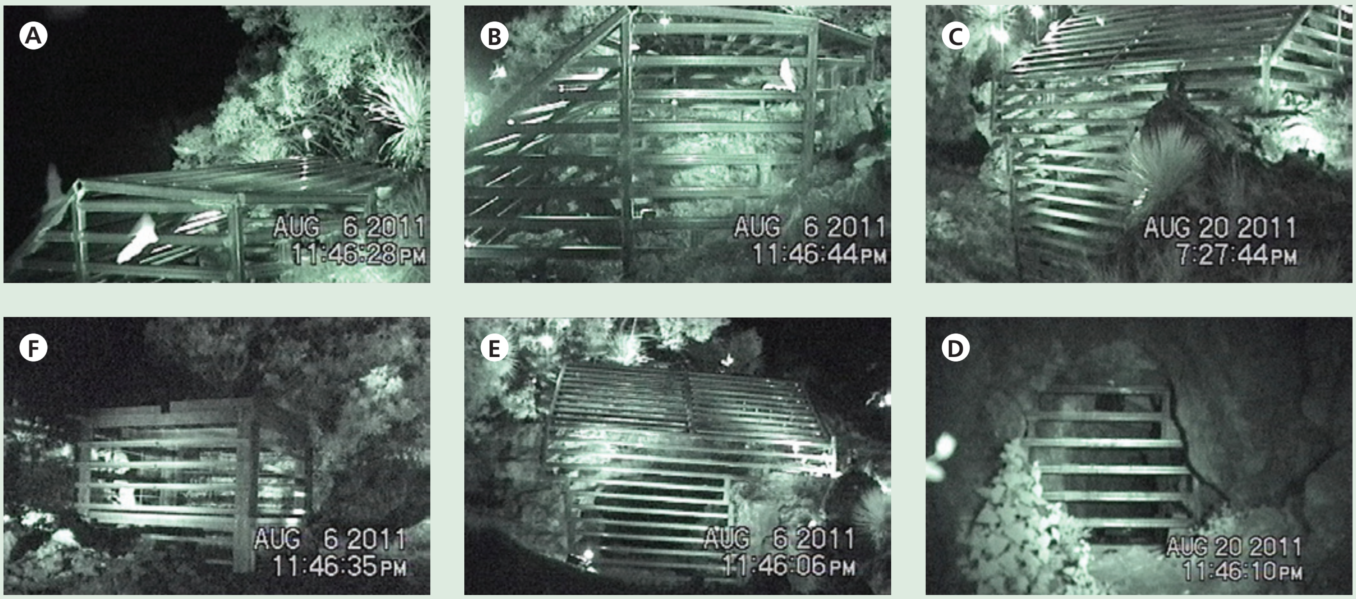
GABRIELLE DIAMOND (5)

Figure 4. The photo series shows three openings into the State of Texas Mine. (A) shows a custom-fit cupola on the main opening. (B) shows a cupola on the west opening and the custom-fit cupola on the main opening. (C) shows the lower adit located southeast of the main opening. All openings have been protected with steel gates (main cupola in 2010, west cupola in 1997, and lower adit in 2010).

Figure 5. (A) This image shows the locations of cameras 1 through 5. (B) The photo at the right shows the location of video camera 6 at the lower adit. Note: In 2010, camera 3 was positioned to capture the entire gate structure and surrounding area; It was later repositioned closer to the front gate to obtain a better view of the front of the gate.

Methods

External video surveys were conducted to monitor lesser long-nosed bat activity at all State of Texas Mine openings using six video camcorders equipped with infrared (IR) capabilities and multiple IR light sources to further illuminate the observation area. Surveyors used IR light sources rather than conventional sources to minimize disturbance to bats and to decrease the likelihood that the lights would induce modifications in the bats' behavior. Video recordings enhance the accuracy of the counts, allow for the calculation of observer/analyst error, and provide a permanent monitoring record. Four cameras set around the main steel gate recorded bat movement through each of the seven gate panels (fig. 5). A fifth camera focused on the west side cupola and a sixth focused on the lower adit. General lighting and video camera placement remained the same throughout the study. Minor enhancements and modifications were made to the layout as needed.



STILL IMAGES BY GABRIELLE DIAMOND, COLLECTED FROM VIDEO

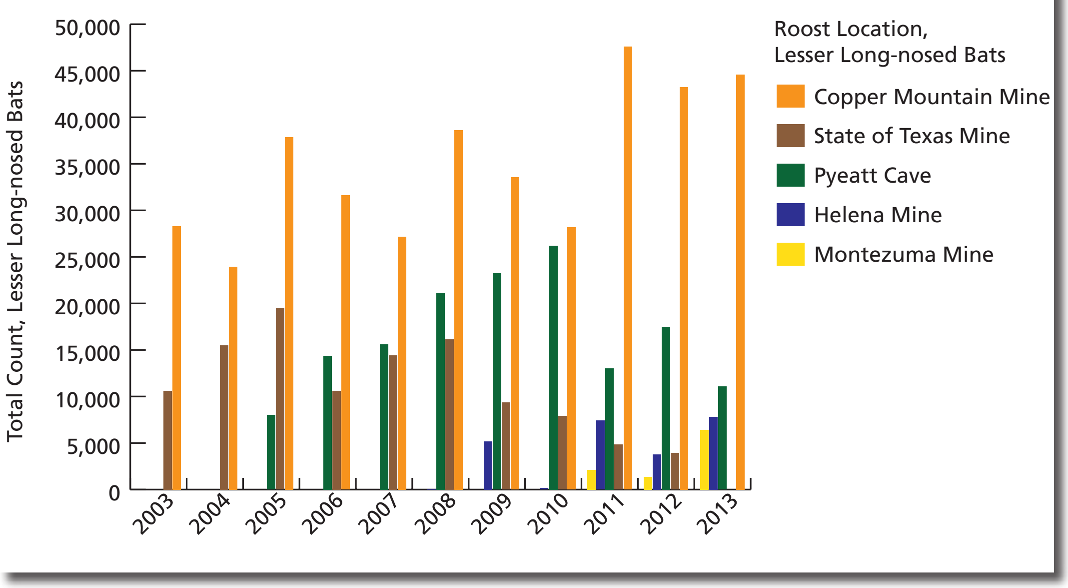
Figure 6. The images show bat emergence as captured by video camera used in the external survey. (Left to right, top to bottom) (A) camera 1 shows panels on top of the main cupola; (B) camera 2 shows a panel on the side of the main cupola; (C) camera 3 shows a panel on the front of the main cupola; (D) camera 4 shows the west cupola; (E) camera 5 shows panels on the top front of the main cupola; (F) camera 6 shows the lower adit bat gate.

To review and analyze the videotapes of bat activity collected during the external surveys at the State of Texas Mine, original taped video data were transferred to hard drives for analysis using digital video (DV) format. The analysis was conducted on a personal computer using the DV file and professional video viewing and editing software. This software allows analysis of a video in slow motion, repeated examination of particular video segments, and the capture of individual frames to JPEG or similar formats. The videos were observed at slower speeds in order to be able to count the number of bats exiting per minute. Sections of the videos were analyzed at quarter, half, or full speed, depending on the amount of bat activity (fig. 6).

Video analysts quantified bat activity per minute at all three openings of the State of Texas Mine during each survey. Since bats have a tendency to exit then reenter mine and cave entrances several times before their final emergence, individual bats were counted exiting the gate ("outs") and entering the gate ("ins") through each of the seven panels that make up the main cupola. The counts for each panel were summed by minute to estimate the total number of bats. Bats per minute and net bats per minute (outs minus ins) were calculated to get a count of the number of bats that emerged from the mine.

To inform the potential effect of the gate on the number of bats exiting per minute (exit rate), this study used survey data from 2003 to 2006 when the cable net was in place on the main entrance to the mine (baseline), survey data provided by the Arizona Game and Fish Department from 2008 when partial and full test gates were used on the main entrance, and survey data collected during this study from 2010 to 2013 for the main cupola. Differences in peak exit rate (the highest observed number of bats exiting per minute), standardized emergence duration (the average number of minutes it took for 1,000 bats to exit), and total number of bats (the colony size or count) were tested using separate generalized linear models. These three variables were considered dependent variables, and the closure type (cable net, partial test gate, full test gate, and cupola) the independent variable. Peak exit rate and standardized emergence duration were natural-log transformed to satisfy normality assumptions of generalized linear models.

We observed a strong correlation between colony size and the rate at which the bats exited the roost: the more bats that were in the roost, the faster they exited per minute and the shorter the duration for the entire colony to exit. The effect of colony size on the bats' behavior was removed from the analysis by calculating the time taken for 25, 50, 75, and 100 percent of the bats to emerge from the roost. This approach produced four variables that were not correlated with the total number of bats and that could provide information on the effects of the gate on exit rates without the confounding influence of the total number of bats. We used



Data sources for graph: The values for the Copper Mountain Mine were obtained from the Arizona Game and Fish Department and the National Park Service. The values for the State of Texas Mine prior to 2010 were obtained from the Arizona Game and Fish Department and Wolf and Dalton (2010), while 2010 through 2013 counts are from this study. Values for Pyeatt Cave in 2005, 2007, 2008, and 2011–2013 were obtained from the Arizona Game and Fish Department. Values for 2006, 2009, and 2010 are from the Sidner and Vernadero Group (2011). Values for the Helena Mine (discovered in 2008) were obtained from WestLand Resources, Inc. Values for the Montezuma Mine were obtained from the Arizona Game and Fish Department.

Figure 7. Comparison of observed peak colony counts reported at Copper Mountain Mine maternity roost and State of Texas Mine, Pyeatt Cave (upper), Helena Mine, and Montezuma Mine post-maternity roosts from 2003 to 2013. *Note:* Colony size at the Copper Mountain Mine, a maternity roost, typically peaks in June. Colony size at the remaining roosts identified here (post-maternity roosts) typically peaks in August.

Welch's correction to control for unequal variance among closure types and the Tukey method to account for the increased probability of finding statistically significant results because of multiple pairwise comparisons among closure types. Differences between closure types were considered statistically significant at $P < 0.05$.

Study findings

Finding 1: Colony size decreased after the cupola was installed and continued to decline during the study, but this decline cannot be attributed to the presence of the cupola with certainty.

The study compared the State of Texas Mine colony size to regional lesser long-nosed bat population trends using general comparisons of observed peak colony size at the State of Texas Mine (a post-maternity roost) with other roosts in southern Arizona. For more than a decade routine counts of lesser long-nosed bat roosts have been conducted simultaneously in mid-August throughout the bats' range in southern Arizona, and the data were compiled by the Arizona Game and Fish Department. Simultaneous counts evaluate regional lesser long-nosed bat trends through direct comparisons of lesser long-nosed bat numbers during the same year. However, the usefulness of roost count data at other sites is limited because no standardized methodology for conducting lesser long-nosed bat roost counts is applied across the species' range. In addition, many variables can affect population trends of this species within its entire range, such as changes in forage availability, drought, and other habitat changes such as wildfires.

Observed peak colony counts at the State of Texas Mine have fluctuated since 2003; its highest count of roughly 19,500 lesser long-nosed bats occurred in 2005 (Wolf and Dalton 2009). During our monitoring period of 2010 to 2013, the observed peak colony size at the State of Texas Mine decreased from a high of approximately 7,900 lesser long-nosed bats in 2010 to 4,800 in 2011, 3,900 in 2012, and 3,500 in 2013.

Comparisons of observed peak colony counts at the State of Texas Mine with those at four other roosts in southeastern Arizona (Copper Mountain Mine, a maternity roost, and Pyeatt Cave, Helena Mine, and Montezuma Mine, post-maternity roosts) show no consistent patterns between years (fig. 7). However, a closer look at counts from roosts at Copper Mountain Mine, Pyeatt Cave, and Helena Mine shows how lesser long-nosed bat colony counts can fluctuate between roosts (table 1, next page).

The Monument Fire, a 30,526-acre (12,353 ha) wildfire on the Coronado National Memorial in mid-June 2011 (AZEIN 2011), burned areas immediately adjacent to the State of Texas Mine. Al-

Table 1. Observed peak colony size change (increasing or decreasing) at four lesser long-nosed bat roosts based on counts conducted from 2004 to 2013

Year	State of Texas Mine (Post-maternity)	Copper Mountain Mine (Maternity)	Pyeatt Cave (Post-maternity)	Helena Mine (Post-maternity)
2004	↑[a] (+4,900)[d]	↓ (−4,400)	No data	No data
2005	↑ (+4,000)[d]	↑[a] (+13,900)	No data	No data
2006	↓ (−8,900)[d]	↑ (+6,300)	↑ (+6,400)	No data
2007	↑ (+3,800)[d]	↓ (−4,400)	↑ (+1,200)	No data
2008	↑ (+1,700)[e]	↑ (+11,400)	↑ (+5,500)	No data
2009	↓ (−6,800)[f]	↓ (−5,100)	↑ (+2,100)	↑ (+5,100)
2010	↓ (−1,400)[g]	↓ (−5,400)	↑ (+3,000)	↓[b] (−5,000)
2011	↓ (−3,000)[c,g]	↑ (+7,600)	↓ (−13,200)[c]	↑ (+7,300)
2012	↓ (−900)[g*]	↓ (−4,300)	↑ (+4,500)	↓ (−3,600)
2013	↓ (−400)[g*]	↑ (+1,300)	↓ (−6,400)	↑ (+4,000)

Notes: Up arrow (↑) represents an increase in lesser long-nosed bat counts from one year to the next while a down arrow (↓) denotes a decrease. The magnitude of change is represented by the difference in the number of lesser long-nosed bats between years and is rounded to the nearest hundred. Gating began at the State of Texas Mine in 2008 with a partial PVC test gate; a full PVC test gate was implemented and remained in place in 2009. The permanent full square-tube steel gate was installed on the main portal at the State of Texas Mine in 2010. The Copper Mountain Mine, Pyeatt Cave, and Helena Mine roosts were not gated during this period.

The accuracy estimates of the colony counts and the exact methodologies used to obtain the counts outside of this study are unknown.

*In 2012 the observed peak in colony size occurred during on 1 September during the last survey of the season. The third survey in 2013 was canceled because of a law enforcement emergency at the memorial, and the observed peak in colony size was on 17 August during the last survey of the season. In 2010 and 2011 we observed a decline in colony size during our last survey of the season, and in 2012 and 2013 we did not observe this decline. Some level of uncertainty always exists because surveys may not be conducted during the actual peak in colony size and observed colony size may not reflect its actual size.

[a]The actual count at the Copper Mountain Mine in 2003 was 28,310; in 2004 it was 23,945 (Tibbitts 2010).

[b]Rain event prevented complete survey.

[c]The Monument Fire occurred in the Huachuca Mountains in mid-June 2011. The fire burned in the immediate vicinity of the State of Texas Mine and in the vicinity of Pyeatt Cave.

[d]Cable net closure installed on the State of Texas Mine main opening.

[e]Partial PVC test gate installed on the State of Texas Mine main opening.

[f]Full PVC test gate installed on the State of Texas Mine main opening.

[g]Cupola gate installed on the State of Texas Mine main opening.

Abandoned mineral lands

By Linda Dansby

Abandoned mineral lands (AMLs) are lands, waters, and surrounding watersheds that contain facilities, structures, improvements, and disturbances associated with past mineral exploration; extraction; processing; and transportation, including oil and gas features and operations, for which the National Park Service takes action under various authorities. During 2010–2013 the National Park Service completed a comprehensive inventory of AMLs that identified 37,050 individual abandoned mine and oil and gas well features in 133 national park units. Of these, 1,799 features (4.9%) already have received long-term remedial action to address human health and safety and environmental problems, and 3,814 features (10.3%) in 76 parks still need remedial action. The remaining 31,437 features were recorded for purposes of general site characterization, but these require no action. The National Park Service estimates that $141 million will be required to address this need over the course of 12 years beginning in 2016. The results of this study are summarized in the September 2014 report published online at http://nature.nps.gov/geology/aml/publications.cfm.

though this fire occurred before lesser long-nosed bats had been observed in the region that year, it is likely one of the causes for the reduction in lesser long-nosed bats at the State of Texas Mine and Pyeatt Cave (also located in the Huachuca Mountains within the Monument Fire burn area) in 2011, because of the fire's impact on the bats' foraging resources in the region.

Finding 2: The cupola did not appear to cause any bat injury or mortality.

The study next focused on bat movement, mortality, and injury. Bats were able to exit through the gate during each survey, and there were no observations of bats injured or killed by direct contact with the gate. The low number of dead bats observed during this study (four bats in four years) should not trigger concern and is likely the result of normal background mortality.

Finding 3: The cupola did not significantly affect the rate at which the bats could exit the roost.

After controlling for correlation between bat exit rate and colony size, we found the bat exit rate with the main cupola to be not significantly different from the rate recorded with the cable net (fig. 8). The peak exit rate was lower during dates with the cupola than during dates with the cable net or test gates, but not significantly lower than with these other closure types (all P > 0.31). Additionally, the standardized emergence duration was slower during dates with the cupola than during dates with the cable net or test gates, but not significantly slower than with these other closure types (all P > 0.47). The time taken for 25, 50, 75, and 100 percent of the total number of bats to emerge on a given night did not differ between dates with the cupola and dates with the cable net (all P > 0.29). We could not test for differences between the cupola and test gates because of low sample size.

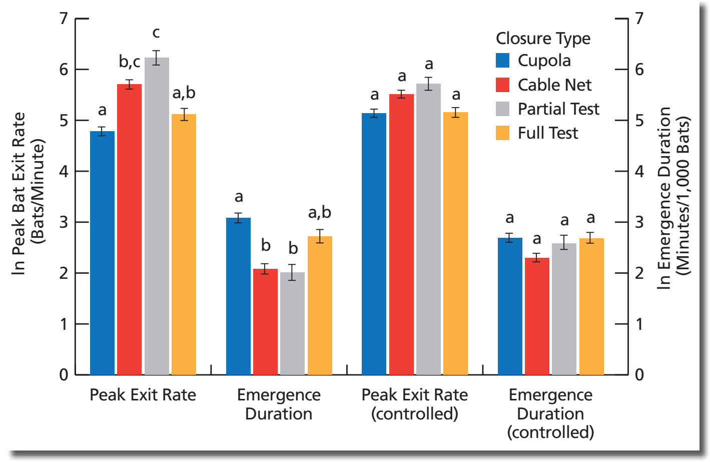


Figure 8. Comparison of peak exit rate and emergence duration among closure types at the State of Texas Mine. The left side of the figure does not control for the number of bats. The right side of the figure presents the results after controlling for the number of bats. Within a variable, bars that do not share a letter are significantly different from each other.

Conclusion

The State of Texas Mine at Coronado National Memorial continues to serve as a roost for lesser long-nosed bats. National Park Service work has led to protection of this roost from human disturbance. This study documented that the bat-compatible gates installed on the roost openings at the mine do not appear to be causing increased injury or mortality to the bats, or to be impeding the bats' ability to exit the roost. However, this study does indicate that lesser long-nosed bat colony size has decreased at the State of Texas Mine. This declining trend is likely related to a number of factors, including changing forage availability, a large wildfire on the Coronado National Memorial in 2011, drought, and other potential habitat changes within the range of this species. Further monitoring of this gate is recommended using the methods designed in this study to ensure that the lesser long-nosed bat colony at the State of Texas Mine continues to thrive. This evaluation provides valuable insight into management of this species on National Park Service lands and throughout this bat's range.

Acknowledgment

In memory of Ronnie Sidner, PhD, 29 September 1950 to 2 August 2014, for her contribution to this study and devotion to bat research, conservation, and education.

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About the authors

Amanda Best *(abest@westlandresources.com), a senior environmental specialist with WestLand Resources, Inc., was the project manager of this study and contributed to the study design and implementation.* ***Gabrielle Diamond****, an environmental specialist with WestLand Resources, was the lead video analyst and assistant project manager of this study.* ***Joel Diamond*** *with the Arizona Game and Fish Department, Wildlife Contracts Branch, was a contributor to the study.* ***Debbie Buecher*** *and* ***Ronnie Sidner****, independent contractors and bat biologists, were contributors to the study design and analysis and conducted the video camcorder survey.* ***David Cerasale****, a senior scientist at WestLand Resources, was a primary contributor to the study and performed the study's statistical analysis.* ***James Tress Jr.****, president of WestLand Resources, was the main contributor to the study design and implementation.* ***Linda Dansby*** *is the NPS Intermountain Region Energy and Minerals Program coordinator and contracting officer's representative.* ***Jason Mateljak*** *is chief of Resource Management, National Park Service—Southern Arizona Group.* ***Adam Springer*** *is Integrated Resources Program manager, Coronado National Memorial.* ***Mike Wrigley*** *is a wildlife biologist with the Intermountain Region, National Park Service.* ***Tim Tibbitts*** *is a retired wildlife biologist, Organ Pipe Cactus National Monument.*

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USGS/KATE SCHOENECKER

Removal of artesian wells in Great Sand Dunes National Park and its aftermath on small mammals, plant cover, and area disturbance by ungulates

Figure 1. The famous sand dunes in Great Sand Dunes National Park and Preserve are a complex product of water and wind. The small-mammal and artesian well study sites are to the left of the dunes and are not visible in this photo.

By Sarah J. Garza, Kenneth R. Wilson, and Gillian Bowser

Abstract

Originally developed for livestock, artesian wells in the San Luis Valley of south-central Colorado have been a stable source of water for cattle and wildlife for more than 100 years. In 2010 the National Park Service capped the wells within the borders of Great Sand Dunes National Park to restore the area to its natural state; concurrently, the park was interested in understanding changes to local biodiversity after well closure. We studied changes to small-mammal population dynamics, plant cover, and area disturbance by ungulates following capping of these wells by comparing species density and survival at capped wells, open well sites (i.e., wells with water), and control sites (i.e., no wells present). Six small-mammal species were captured (1,150 individuals), but only Ord's kangaroo rat (*Dipodomys ordii*) and pocket mouse species (*Perognathus* sp.) had sufficient captures to estimate parameters. In general, there was little difference in these species' density and survival among well types. Plant cover and level of disturbance by ungulates best predicted density for the kangaroo rat and pocket mouse, while year of study influenced survival of both species. There was no difference in native plant cover at different well sites, but open well sites had significantly higher levels of disturbance. Our results suggest that in the short term, small-mammal population dynamics have changed little after well capping for the most common small-mammal species.

Key words

artesian well, density, Great Sand Dunes National Park, mark-recapture, small mammals, survival

THROUGHOUT THE PASTORAL HISTORY OF THE United States, artificial water sources have been used to support humans, livestock, and agriculture in arid regions. This increased water availability has affected ecosystems by altering forage abundance and concentrating livestock and wildlife (Andrew 1988; Brooks et al. 2006). The resulting combination of trampling, grazing, and high densities of ungulates, especially in arid ecosystems, can produce a gradient of disturbance, with the greatest intensity nearest to the water source (Nash et al. 1999). This disturbance gradient can be of concern, especially in protected arid regions. Although recent research on artificial water sources has focused on everything from stream recovery (Rigge et al. 2013) to soil conditions in relation to grazing intensity (Augustine et al. 2012), few studies have actually examined the effects of water removal on these disturbance regimes. This knowledge is important for the management of natural resources, especially in light of climate change and predicted drought increase in some areas (Cayan et al. 2010).

In south-central Colorado, Great Sand Dunes National Park and Preserve provides an opportunity to study the removal of artificial water sources in an arid ecosystem (fig. 1). Prior to becoming a national monument in 1932, this area was developed for ranching operations with 24 artificial artesian wells drilled into the underlying confined aquifer to provide water for local cattle herds. Areas around these well sites were highly disturbed from frequent visitation by cattle and wild ungulates such as elk (*Cervus elaphus*) and, more recently, ranched bison (*Bison*

Great Sand Dunes National Park and Preserve provides an opportunity to study the removal of artificial water sources in an arid ecosystem.

COLORADO STATE UNIVERSITY AND USGS/SARAH J. GARZA

Figure 2. Bison drink from a well site in The Nature Conservancy's Zapata Ranch. Investigators sought to determine if capping wells in the adjacent national park had an effect on the local small-mammal population dynamics.

bison, fig. 2). When the national monument became a national park in 2004, the National Park Service (NPS) acquired land rights and, in 2010, capped all artesian wells on NPS lands (10); 14 wells remain open on adjacent lands owned by The Nature Conservancy. Along with maintaining the natural hydrological system of the sand dunes, the National Park Service is interested in eliminating the "piosphere effect," the combined influence of grazing and trampling on vegetation and soil that results in highly denuded zones of landscape, such as those around artificial water sources (Lange 1969). We designed our study to focus on changes in ungulate disturbance following the capping of wells and its aftereffects on small-mammal population dynamics and plant cover as a proxy for the ecological effects of removing artificial sources of water. Changes in small-mammal population dynamics can often serve as an ecological indicator of alterations in ecosystem structure and function (Carey and Harrington 2001). Only a few empirical studies have focused on small mammals, denuded zones, and artificial sources of water. For example, small-mammal species diversity was not altered at watering sites in semiarid scrub communities of southern New Mexico (Burkett and Thompson 1994), while another study (James et al. 1997) documented decreases in small-mammal abundances near water sources in the arid grasslands of Australia.

Piosphere plant communities are characterized by early stages of ecological succession, such as large areas devoid of plant cover (Fusco et al. 1995) and decreased plant species composition (Fernandez-Gimenez and Allen-Diaz 2001). In desert ecosystems, the types of emerging plant species related to ecological succession at artificial watering sites can vary greatly (Andrew 1988; Fusco et al. 1995). For example, in the Mojave Desert, California, the earliest stage of succession at watering sites was characterized by exotic plant species on bare ground (Brooks et al. 2006). In the Chihuahuan Desert, New Mexico, livestock created nutrient-rich patches near water that supported species of native annual plants that were rare or absent in other areas (Nash et al. 1999).

In this study, we characterized the short-term response of small-mammal and plant communities to capping of artesian well sites by comparing density, survival (small mammals), and cover (plants) across three site types: capped well sites, wells with water (open well sites), and control sites (selected sites intended to represent average land settings not influenced by open water sources). Based on previous studies of ungulate distribution around artificial water sources (Thrash et al. 1993; Smit et al. 2001) and adaptations of small mammals in arid ecosystems (Bich et al. 1995; Davidson et al. 2010; Germano et al. 2011), we hypothesized that small-mammal population dynamics would be related to ungulate disturbance intensity levels and only indirectly to the water source itself. We predicted that capping artesian wells would reduce disturbance, improve habitat, and result in higher small-mammal density and survival estimates relative to open well sites. Additionally, we predicted that capping well sites would affect plant cover because differences in ungulate use create differences in disturbance intensity (Lange 1969) that can influence plant community development (Leicht-Young et al. 2009). Specifically, we expected native plant cover to be greatest at the capped well sites because of less disturbance by ungulates.

Methods

All study sites were located in the San Luis Valley (fig. 3), a high-elevation closed basin valley of approximately 21,000 km² (8,108 mi²) in Colorado and New Mexico. Key grass species included blue grama (*Bouteloua gracilis*), Indian rice grass (*Oryzopsis hymenoides*), needle and thread grass (*Hesperostipa comata*), and false buffalo grass (*Monroa squarrosa*), while key shrubs were

MAP BY OFFICE OF EDUCATION AND OUTREACH; DATA FROM GREAT SAND DUNES NATIONAL PARK; BASE MAP BY NPS/HARPERS FERRY CENTER

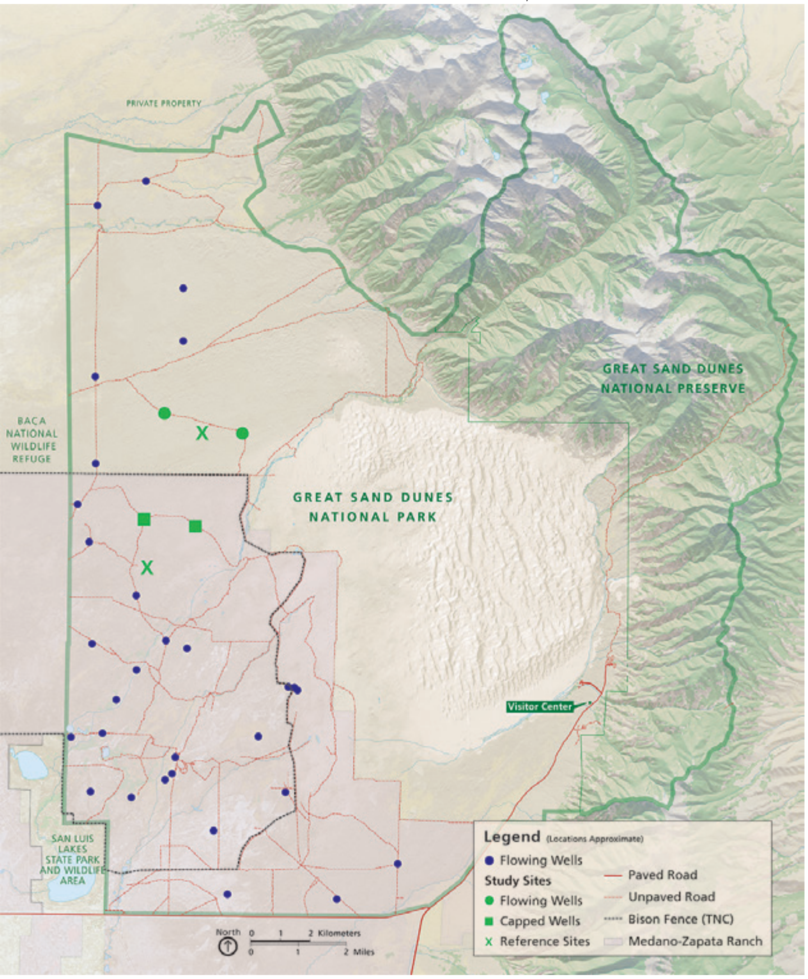

Figure 3. Location of artesian well sites and control sites studied in Great Sand Dunes National Park and The Nature Conservancy's Zapata Ranch, south-central Colorado, 2011–2012.

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Figure 4. (A, top) An open well on The Nature Conservancy's Zapata Ranch, Colorado, and (B, bottom) a capped well site in Great Sand Dunes National Park.

rubber rabbitbrush (*Ericameria nauseosus*), sagebrush (*Artemisia* sp.), and yucca (*Yucca glauca*). Part of our study occurred on the fenced 200 km^2 (77 mi^2) northern portion of The Nature Conservancy's Zapata Ranch where approximately 2,000 introduced bison are ranched. Native elk, mule deer (*Odocoileus hemionus*), and pronghorn (*Antilocapra americana*) move freely across Great Sand Dunes National Park and the Zapata Ranch—due to a bison fence, there are no free-ranging bison inside the park boundaries.

We studied small mammals and plants at two capped wells, two open well sites, and two control sites in Great Sand Dunes National Park and on The Nature Conservancy's Zapata Ranch (fig. 3). Sites were not randomly located because site selection was limited by accessibility, similarity of water containment structure types, and similarity of habitats; in addition, capped wells could not naturally have ceased waterflow prior to capping in 2010. Open wells (fig. 4A) were heavily trampled by animals and had less vegetation around the tanks than capped wells (fig. 4B) and control sites (see Garza 2013 for details).

We measured percentage of total plant cover and disturbance intensity level once a month using a 1 m^2 (11 ft^2) sampling frame placed at intervals of 10 m (33 ft) along each transect line of the trapping web. Evidence of disturbance included trampling (areas of compacted sand and no plant cover), presence of tracks, and flattened shrubs (Howe and Baker 2003). Four disturbance levels were defined based on intensity within the sampling frame: 0 = none, 1 = mild (bare ground was < 25% of quadrat and presence of ungulate tracks), 2 = intermediate (bare ground was ~50% of quadrat and presence of ungulate tracks), and 3 = extreme (bare ground was > 50% of quadrat and presence of ungulate tracks). The 10 sampling frames per transect line resulted in 120 samples per site, and these were averaged for each sampling period to compute an overall estimate of plant cover and disturbance intensity level.

Figure 5. The study employed point sampling, which combines the use of live traps to detect small mammals and modeling software that estimates species density and survival. Introduced ranched bison from the Zapata Ranch graze the area around one of the open well sites.

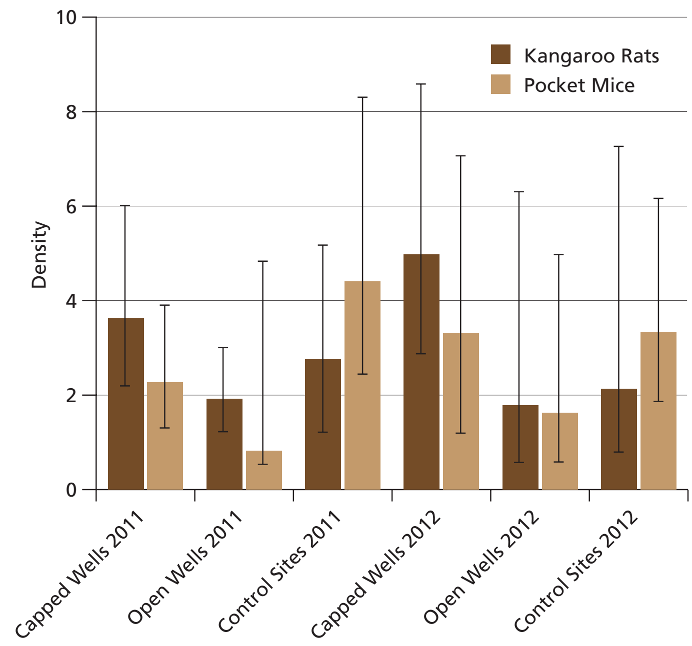

Figure 6. Average monthly density (number of individuals per m^2 log-based 95% confidence intervals, n = 6 in 2011, n = 8 in 2012) of Ord's kangaroo rat (*Dipodomys ordii*) and pocket mouse (*Perognathus* spp.) in Great Sand Dunes National Park and The Nature Conservancy's Zapata Ranch, Colorado. The sample size increased in 2012 due to additional sampling sessions.

We captured and fitted ear tags to small mammals from May to August, 2011 and 2012 (Monel model 2001-1, National Band and Tag Company, Newport, Kentucky). We used a trapping web design (Anderson et al. 1983; Buckland et al. 1993; Burnham and Anderson 2002) of 100 Sherman live traps (23 × 8 × 9 cm [9 × 3 × 4 in], fig. 5) that consisted of 12 equally spaced lines of traps radiating from a central point near the wellhead.

We coupled the trapping-web design with mark-recapture methods to calculate estimates of density and survival of the most common species. Mark-recapture consists of capturing, marking, and then releasing animals to be captured at a later occasion. We used distance sampling (Buckland et al. 1993) to estimate small-mammal density using the initial captures of animals and the point estimate feature in the computer software DISTANCE. Distance sampling comprises a set of methods in which distances from a point to multiple animal detections are recorded and the density is estimated (Buckland et al. 1993). Mark-recapture data were used to estimate survival in the computer software Program MARK (White and Burnham 1999).

We modeled these density and survival estimates by species as a function of (1) well site type, (2) percentage of total plant cover, (3) level of disturbance, and (4) year of study to determine which factors influenced small-mammal populations. We also included an "intercept-only" model to determine if none of the variables explained the variation of the rates.

We used Akaike's Information Criterion (AIC) as a statistical measure of the relative quality of a statistical model for a given set of data. We used AIC_C, the small sample size adjustment for AIC (Akaike 1973; Hurvich and Tsai 1989), to select the models that best fitted the sample data. The models with the lowest AIC_C represented the variables that best explained differences in the density and survival of the small mammals. We were also able to calculate the relative importance of each variable by summing the AIC_C weights for each variable across all models in the data set. The larger the estimate of relative importance, the more important the variable in explaining the density and survival estimates. Variables with values ≥ 0.5 are considered important.

Results

Vegetation and disturbance

Average plant cover (n = 7) was greatest at capped well sites ($\overline{X}$ = 10.87%, SE = 0.32%), lowest at open well sites ($\overline{X}$ = 9.73%, SE = 0.31%), and intermediate at control sites ($\overline{X}$ = 10.00%, SE = 0.25%). These differences were not considered significant. Average disturbance intensity levels were 1.10 (SE = 0.02), 1.21 (SE = 0.03), and 1.08 (SE = 0.01) at capped, open, and control sites, respectively. Average monthly temperature and precipitation from

Table 1. Small mammals captured over 18 total trap nights in Great Sand Dunes National Park and The Nature Conservancy's Zapata Ranch, Colorado

Species	Capped Well Sites 2011	Capped Well Sites 2012	Open Well Sites 2011	Open Well Sites 2012	Control Sites 2011	Control Sites 2012
Kangaroo rat, *Dipodomys ordii*	83	179	170	78	90	57
Pocket mouse, *Perognathus* spp.[1]	27	30	10	52	33	94
Thirteen-lined ground squirrel, *Spermophilus tridecemlineatus*	1	3	2	15	17	23
Northern grasshopper mouse, *Onychomys leucogaster*	5	6	3	3	28	8
Deer mouse, *Peromyscus maniculatus*	0	6	2	7	3	12
Least chipmunk, *Tamias minimus*	0	1	0	0	1	1
Total Individuals	116	225	187	155	172	195
Total Species	4	6	5	5	6	6

[1]Two species of pocket mouse, *Perognathus apache* and *P. flavus*, potentially were captured but were difficult to identify without examining skulls and teeth; therefore, pocket mice were identified only to genus.

Note: Data were collected over three days per month for three to four months each year of the study.

May to August were 17°C (SE = 1.23) and 21 mm (SE = 5.52) in 2011 and 18°C (SE = 0.82) and 30 mm (SE = 4.14) mm in 2012. Average rainfall during the two years of the study was 7 mm (0.28 in) below average (Western Regional Climate Center 2013).

Small mammals

From 2011 to 2012, we captured a total of 1,150 individuals of six potential species: 441 at capped wells, 342 at open wells, and 367 at control sites (table 1). Ord's kangaroo rat (*Dipodomys ordii*) and pocket mouse (*Perognathus* sp.) accounted for 66% (757) and 21% (246) of individual captures, respectively. The remaining species represented 5% or less of total captures: thirteen-lined ground squirrel, *Ictidomys tridecemlineatus* (58); northern grasshopper mouse, *Onychomys leucogaster* (51); deer mouse, *Peromyscus maniculatus* (30); and least chipmunk, *Tamias minimus* (3). The two potential species of pocket mouse in the study area, Apache pocket mouse (*Perognathus apache*) and silky pocket mouse (*P. flavus*), are difficult to distinguish in the field; therefore all pocket mice were categorized only to genus.

Only kangaroo rats and pocket mice had a sufficient number of captures for density and survival estimates. Average monthly density for kangaroo rats was greatest at capped well sites, followed by control sites and open well sites (fig. 6); however, these were not significantly different.

Models that best explained kangaroo rat density included percentage of total plant cover and well site type ($\Delta AIC_C \leq 2$) (table 2). Only percentage of plant cover was important to kangaroo rat density (relative importance = 0.62). Density tended to increase with increasing plant cover ($\hat{\beta} = 0.02$; lower bound 95%confidence interval [CI] = 0.01, upper bound 95% CI = 0.04). All other variables had no significant effect on kangaroo rat density.

Table 2. Effect of well site type and habitat characteristics on monthly densities of selected small-mammal species in Great Sand Dunes National Park and The Nature Conservancy's Zapata Ranch, Colorado, 2011–2012

Species	Model/Variable	ΔAIC_C	AIC_C Weight	K
Kangaroo rat				
	Percentage of Total Plant Cover	0	0.34	2
	Well Site Type	1.16	0.19	2
Pocket mouse				
	Intensity Level of Disturbance	0	0.19	2
	Well Site Type	0.13	0.18	2
	Intercept-Only	0.28	0.17	1
	Year + Disturbance	1.24	0.10	3
	Cover + Disturbance	1.53	0.09	3

Notes: The models with the lowest AIC_C represent variables with the most effect on the monthly densities.

Results are for the difference in Akaike's Information Criterion corrected for small sample sizes and applied to top-ranked models ($\Delta AIC_C \leq 2$), model weight (AIC_C Weight), and number of parameters in the models (K). Well sites include capped, open, and control. Disturbance level was 0–3. Average monthly plant cover was 0–100%. Data are for 2011 and 2012.

Table 3. Estimates of monthly survival rate for selected small-mammal species at study sites in Great Sand Dunes National Park and The Nature Conservancy's Zapata Ranch, Colorado

		Year			
		2011		2012	
Species	Site Type	Survival Rate	Confidence Interval	Survival Rate	Confidence Interval
Kangaroo rat					
	Capped Well	0.41	0.23–0.61	0.48	0.28–0.69
	Open Well	0.30	0.14–0.53	0.37	0.13–0.70
	Control	0.33	0.19–0.51	0.40	0.19–0.65
Pocket mouse					
	Capped Well	0.55	0.33–0.75	0.78	0.47–0.93
	Open Well	0.56	0.34–0.76	0.78	0.46–0.94
	Control	0.56	0.34–0.74	0.79	0.46–0.93

For pocket mice, density estimates were highest at control sites, followed by capped well sites and open well sites (fig. 6), but again the differences between site types were not significant. The five top models explaining pocket mouse density had similar AIC_C weights and included level of disturbance, well site type, and the intercept-only models (table 2). None of the variables had importance values ≥ 0.5; therefore, these variables could not be considered influential to pocket mouse density.

Estimates of monthly survival for kangaroo rats were greatest at capped well sites, where individuals had a 41% chance of survival from month to month, but differences among the three site types were insignificant (table 3). The most important variable was year of study, as kangaroo rat survival increased measurably from 2011 to 2012. For pocket mouse estimates of survival, year was also the most important variable. Estimates of monthly pocket mouse survival in 2012 were nearly twice those of 2011, but again there was no significant difference among well types (table 3). Overall, we found no differences in small-mammal populations following the removal of artificial artesian wells.

Discussion

Over the two years of our study, we did not detect significant differences in small-mammal species density and survival, nor did we see significant changes in plant cover at capped artesian well sites compared with open wells for the two most common species, Ord's kangaroo rat and pocket mouse. Other studies have documented increased rodent presence and survival in areas that are structurally open and slightly disturbed (Kelt et al. 2005; Tietje et al. 2008; Schorr et al. 2007), but the amount of disturbance at our well sites might have been more severe than in these studies. Density and survival of small mammals tended to vary more by year than by well site type, which may be linked to differences in annual precipitation between years during our study and the overall lower-than-average precipitation during both years. The national park has experienced drought conditions for the past six years and rain levels were lower than expected during both years of the study, almost 7 cm (2.8 in) below average (Western Regional Climate Center 2013). For example, in a rainfall manipulation experiment, Kray et al. (2012) found that reduced rainfall in the San Luis Valley over a two-year period significantly decreased native grass species cover, an important source of food for small mammals (Davidson et al. 2010; Germano et al. 2011). If small mammals had relied directly on the water from the wells, then their numbers would likely have been shown to decline markedly after the wells were capped. However, this was not the case.

Native plant cover was not significantly different at capped well sites compared with open well sites and control sites. Native cover varied more by year of the study and again, variation in annual precipitation may have played a more important role than well site types in these two years. The seeds of various desert plant species require varying amounts of rain for germination and seedling establishment (Gutterman and Gozlan 1998), and after insufficient rainfall, seedlings can suffer irreversible damage from dehydration stress, resulting in lower seed availability. Overall, these results suggest no discernible changes in plant community composition that may be related to the short-term impacts of capping artesian well sites.

The National Park Service is interested in eliminating the . . . combined influence of grazing and trampling on vegetation and soil that results in highly denuded zones of landscape, such as those around artificial water sources.

Conclusion

Our work provides park resource managers with an initial look at the restoration dynamics surrounding artificial water sources, and also may be useful to other land and resource managers interested in similar restoration efforts. These interpretations, however, should be tempered because of the limitations of this study. Although our observations suggest that capping artificial water wells in the Great Sand Dunes ecosystem results in no significant changes in small-mammal population dynamics or native plant cover, it is also possible that a trend may be difficult to discern from so short a study period, arrangement of the wells, and the presence of bison at some sites but not others. These limitations make it difficult to derive conclusions that are not in part speculative. Follow-up work will be needed to fully understand the long-term ecological effects of capping wells.

The recovery of arid grasslands from a long-term disturbance can take decades (Daubenmire 1975; Rickard and Sauer 1982) and the artesian wells in our study were in use for more than 100 years, so it is understandable that recovery may take many more years. Furthermore, despite the absence of open water, we observed continued visitation of the capped well sites by elk, and the resulting disturbance from trampling may further delay habitat community recovery. Certainly, the influence of the well sites is small relative to the surrounding natural habitats; thus restoration of these well sites is probably not necessary to ensure that small-mammal biodiversity is maintained in Great Sand Dunes National Park.

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About the authors

Sarah J. Garza *is a research associate with the Department of Biology, Colorado State University, in Fort Collins. She can be reached at Sarah.Garza@rams.colostate.edu.* ***Kenneth R. Wilson*** *is a professor and head of the Department of Fish, Wildlife, and Conservation Biology at Colorado State University.* ***Gillian Bowser*** *is a research scientist and scholar with the Natural Resource Ecology Laboratory at Colorado State University.*

PS

Vascular plant hyperdiversity in high-elevation riparian communities of National Park Service units in the Klamath Network

By Sean B. Smith and Daniel A. Sarr

Abstract

We analyzed vascular plant species richness in 0.1 ha (0.25 acre) plots collected in probabilistic samples of upland and riparian systems of four National Park Service units, Crater Lake National Park (NP), Lassen Volcanic National Park (NP), Redwood National and State Parks (NSP), and Whiskeytown National Recreation Area (NRA), to compare patterns of vascular plant species diversity. We found that riparian plots were richer in species than upland environments in all four parks. Contrary to the typical global pattern of declining species richness with increasing elevation, we noted an increase in average richness of riparian plots from 0 to 2,382 m (7,815 ft) elevation, and a hyperdiversity of species in riparian plots at Crater Lake NP and Lassen Volcanic NP (riparian plots had over three times the mean species richness of upland plots). Higher-elevation riparian plots had a higher proportion of native herbaceous perennial species than lower-elevation riparian plots. The rich flora of moisture- and cold-adapted herbs in riparian areas of Crater Lake NP and Lassen Volcanic NP suggests that these montane riparian zones act as refugia for a rich pool of species that were likely more widespread in colder periods of the Pleistocene, and have since been preserved in these low-latitude refuges by distinct microclimatic and hydrologic conditions that limit warming and drying.

Key words

high-elevation riparian, hyperdiversity, inventory and monitoring, plant diversity, refugia, riparian

WITHIN PARKS AND PROTECTED AREAS, AS elsewhere, riparian areas often comprise a small portion of the total area, but a notable proportion of native plant diversity (Goebel et al. 2003). The drivers of riparian diversity span multiple scales, from local disturbances to broad-scale gradients in climate and geology (Baker 1989; Gregory et al. 1991; Bendix 1994; Sarr and Hibbs 2007).

In the United States, national parks and other protected areas are known to disproportionately represent high-elevation and lower-productivity terrain (Scott et al. 2001), and have been shown to be less biodiverse than private lands (Hansen and Rotella 2002). For vascular plants, species diversity typically declines sharply with increasing elevation (Glenn-Lewin 1977) or, in arid environments, shows a unimodal pattern with elevation, with maximum vascular plant diversity at middle elevations (Whittaker and Niering 1965). These empirical patterns suggest that high-elevation environments protect fewer species than comparable areas at low elevation. However, while many studies have focused on upland plant communities, not much is known about the patterns of riparian plant diversity across elevation gradients.

Figure 1. The Klamath I&M Network consists of six national park units, including four studied for vascular plant species richness over an elevation gradient.

The Klamath Network, composed of six National Park Service units in southern Oregon and northern California (fig. 1), encompasses a rich array of plant communities, from maritime coastal forests to upper montane and alpine environments. Riparian areas span much of the gradient from sea level to the subalpine zone, allowing a comparison of elevation effects on upland and riparian diversity. In this study we compared the diversity of upland and riparian vegetation across an elevation gradient of approximately 0–2,382 m (0–7,815 ft) and spanning four parks of the Klamath Network, listed from lowest to highest average elevation: Redwood National and State Parks, Whiskeytown National Recreation Area, Crater Lake National Park, and Lassen Volcanic National Park.

Glossary

Riparian: Those locations near a stream or river that are affected by hydrologic processes, or which disproportionately affect the stream through shading, litter fall, or other influences. Riparian areas may be entirely or partially wetlands, depending upon the hydrology, soils, and vegetation present.

Upland: Those locations away from streams, lakes, or other water bodies, where local climatic and geologic processes control vegetation, and characteristic wetland soils and plant species are absent.

Wetland: Those locations that typically have hydrology, soils, and vegetation that are indicative of saturation with water for substantial periods of the growing season.

Methods

We used data collected by the Klamath Network Inventory and Monitoring Program in four parks from 2011 to 2013. All data were collected using the Klamath Network Vegetation Monitoring Protocol (Odion et al. 2011). Full field methods are provided in the protocol. We present abbreviated methods here.

Site selection and fieldwork

In 2011, we sampled 26 upland and 21 riparian sites (elevation range 4–694 m [13–2,277 ft]) at Redwood NSP. Our 2012 effort resulted in 18 upland and 14 riparian sites (elevation range 1,798–2,382 m [5,899–7,815 ft]) at Lassen Volcanic NP, and 21 upland and 15 riparian sites (elevation range 288–1,313 m [945–4,308 ft]) at Whiskeytown NRA. In 2013, we sampled 26 upland and 20 riparian sites (elevation range 1,382–2,061 m [4,534–6,762 ft]) at Crater Lake NP. All plots were sampled in designated sampling frames, which were located in riparian or upland sites using a spatially balanced and probabilistic sampling design. For safety and accessibility, sites were excluded from areas more than 1.0 km (0.6 mi) from a road or trail. We also avoided steep slopes (>30°) and areas otherwise too dangerous for field crews to sample repeatedly (e.g., barren lava flows, talus slopes). With one exception, at Whiskeytown NRA, because of the dangers posed by the presence of illegal *Cannabis* cultivation gardens, all sites were sampled < 150 m (492 ft) from a road or trail. All riparian sites were located along perennial streams derived from the USGS National Hydrography Dataset (NHD).

Our plot design was adapted from methodologies of the Carolina Vegetation Survey (Peet et al. 1998) and uses a hierarchical nested Whittaker plot. For upland sites, we used a 20 × 50 m (66 × 164 ft) plot. For riparian sites, we attempted to establish one 10 × 50 m (33 × 164 ft) belt on each stream bank. If one of the stream banks was inaccessible, rather than reject the site we used a 10 × 100 m (33 × 328 ft) plot. Keeley and Fotheringham (2005) demonstrated that such variation in plot shape does not typically affect diversity studies if plot sizes are similar. All upland and riparian plots sample a total of 0.1 ha (0.25 acre). At each plot, all vascular plant species at a site were identified, environmental data and geographic coordinates were recorded, and unknown specimens were collected for later identification.

Data analysis

All data were collected and stored in a custom-made Microsoft Access database. More complex data analyses were performed with the R statistical package (R Core Team 2013). Scatterplots and regression analyses were performed in R using the ggplot2 package.

Results

Here we analyze and report only species richness (number of vascular plant species) for all 0.1 ha (0.25 acre) plots. Across all parks mean species richness for riparian sites was 62 vascular plant species (± SD 17.8), while mean richness for upland sites was 23 (± SD 14.6). This difference was highly significant (analysis of variance $F_{1,159} = 225.8$, $p < 0.001$). Although riparian plots had higher species richness than upland plots at all parks, the magnitude of difference varied markedly across parks (fig. 2). In particular, the riparian areas in the two higher-elevation Cascades Range parks, Lassen Volcanic NP and Crater Lake NP, had over three times as many species as comparable upland plots. Nonnative species were observed more frequently at plots in the lower-elevation parks (34% at Redwood NSP and 83% at Whiskeytown NRA) than at the higher-elevation parks (34% at Lassen Volcanic NP, and 26% at Crater Lake NP). Viewed across all species recorded

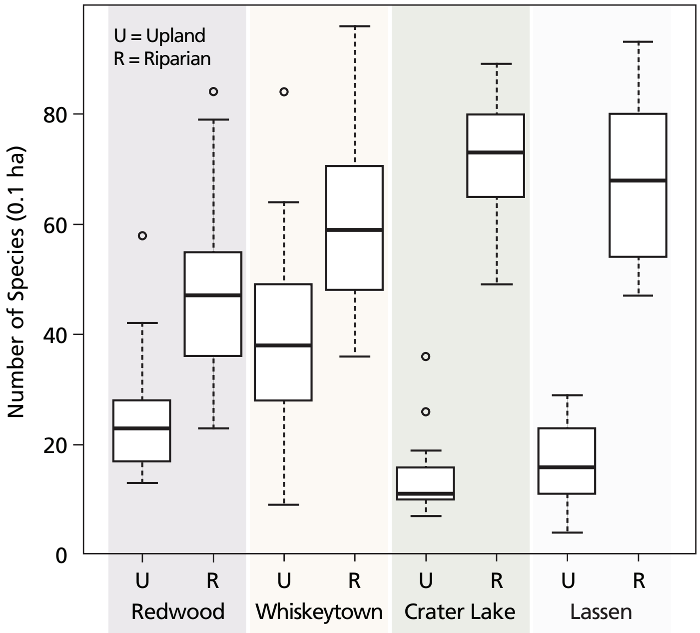

Figure 2. The box plots show mean species richness of upland (U) and riparian (R) plots. Parks are shown in order of increasing average elevation, from left to right. All riparian plot mean species richness is significantly different from that of upland (F > 13.9, $p < 0.001$) plots. Bottom and top of boxes show 25th (first quartile) and 75th (third quartile) percentiles, respectively. Whiskers show maximum and minimum, except when outliers are present. Outliers are shown as hollow dots and are 1.5 times below the first quartile and 1.5 times above the third quartile, respectively.

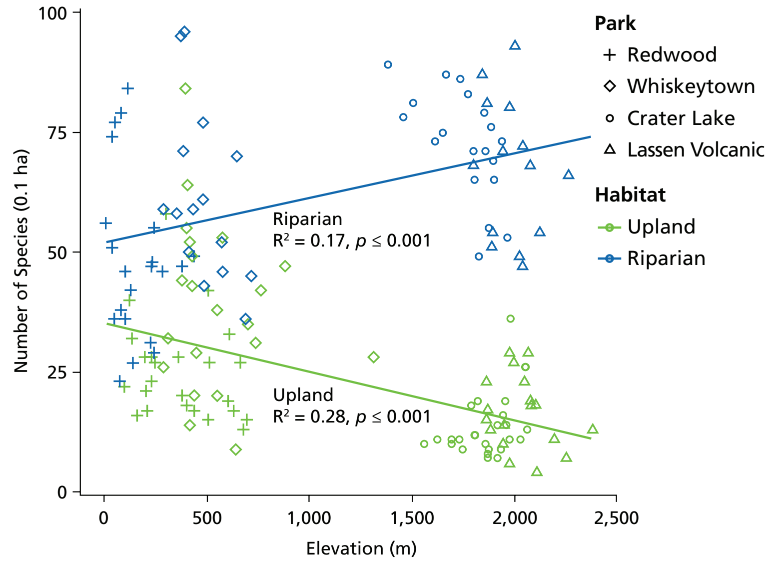

Figure 3. The scatterplot and regression lines show species richness of both riparian and upland 0.1 ha (0.25 acre) plots from the four parks in the Klamath Network.

in our field sampling, percentages of nonnative species richness were much smaller at higher-elevation parks (0–6% at Lassen NP and 0–11% at Crater Lake NP versus 0–70% at Redwood NSP and 0–32% at Whiskeytown NRA).

Scatterplots and univariate regression models of species richness against elevation showed opposing patterns for upland and riparian plots (fig. 3). Whereas species richness significantly declined with elevation in upland plots ($F_{1,89} = 35.4$, $R^2 = 0.28$, $p < 0.001$), it significantly increased ($F_{1,68} = 14.8$, $R^2 = 0.17$, $p < 0.001$) in riparian plots. Rather than showing declines in species richness with increasing elevation, as is recorded in most field studies of vascular plants in North America (Glenn-Lewin 1977), and in adjacent upland plots in the same parks, the high-elevation riparian plots were, in fact, hyperdiverse. It is important to emphasize that the hyperdiversity in high-elevation riparian areas that we recorded is composed primarily of native species; these samples had the lowest frequency and lowest cumulative richness of nonnative plant species.

Paradoxically, when analyzed separately for each park, plots showed minor and typically insignificant declines in species richness with increasing elevation, in both upland and riparian sampling frames (data not shown). Thus, the major divergence in diversity between upland and riparian areas appears to be manifested at landscape scales across multiple parks. The relationship between plot latitude and species richness, which is noted in most studies of vegetation (Sarr et al. 2005), was significant and negative for univariate regression models of upland plots ($F_{1,89} = 15.8$, $R^2 = 0.15$, $p < 0.001$), but not for riparian plots ($F_{1,68} = 2.4$, $R^2 = 0.02$, $p = 0.12$). This suggests that riparian areas of the Klamath Network

The riparian areas in the two higher-elevation Cascades Range parks, Lassen Volcanic NP and Crater Lake NP, had over three times as many species as comparable upland plots.

parks are regionally decoupled from widely reported biogeographic patterns (i.e., that vascular plant diversity declines with elevation and latitude) (Sarr et al. 2005; Guo et al. 2013).

Because we sampled across three years, it is possible that climatic variation was associated with some of the landscape variation in diversity we recorded. Climate data for 2011 and 2012 were close to long-term climatic averages (PRISM Climate Group 2014), but 2013, when we sampled Crater Lake NP, was the start of a severe drought in the Klamath region. Upland plots for Crater Lake NP showed the lowest diversity of all plots, whereas riparian sites still had high richness (fig. 2), so the impacts of the drought on diversity are unclear.

To better understand the nature of such high species richness in montane riparian zones, we partitioned the species into life history groups (i.e., annual or perennial and tree, shrub, forb, or graminoid) of all species as a percentage of overall flora we observed across the sample frame in each park (fig. 4). Because these aggregate data were not replicated and thus not tested for significance, we cannot make statistical inferences about overall species composition across comparable landscapes. Nevertheless these data illustrate the general floristic character of the high-elevation riparian communities we sampled. First, at riparian sites at the higher-elevation parks, Crater Lake NP and Lassen Volcanic NP, a higher percentage of the flora is perennial forbs and graminoids. Second, in low- and mid-elevation parks, Redwood NSP and Whiskeytown NRA, a higher percentage of the flora is woody species and annual forbs and graminoids.

Discussion

Efforts to conserve biological diversity are always imperfect, as we lack the resources to protect all lands and to control all land uses. Geographic location is therefore highly important, and the search for biodiversity hotspots is a major goal of conservation planning (Scott et al. 2001; Myers et al. 2000). The high-elevation lands that make up most western park landscapes were carved from the most remote and typically least agriculturally productive parts of the landscape, and have usually been found to be poorer in species than lower-elevation environments for most native taxa studied (Scott et al. 2001; Hansen and Rotella 2002). This does not appear to be the case with vascular plants in riparian areas at Crater Lake NP and Lassen Volcanic NP. These high-elevation parks protect a very rich riparian flora that is also highly distinctive in the larger landscape. In particular, these riparian environments are hotspots for graminoids like sedges (*Carex* spp.), rushes and woodrushes (*Juncus* and *Luzula* spp.), and perennial grasses (*Deschampsia*, *Glyceria*, and *Calamagrostis* spp.), as well as a rich

A fundamental driver of these systems appears to be winter snowpack, which delays runoff of winter precipitation and allows it to continually recharge groundwater reservoirs and feed perennial streams through the summer, which in turn harbor the rich, predominantly native riparian flora.

array of moisture-loving forbs (*Senecio*, *Aconitum*, and *Viola* spp.). The rich riparian flora of the higher-elevation parks is also made up predominantly of native species, more so than in the lower-elevation parks.

The presence of such moisture- and cold-adapted plant species in the quasi-Mediterranean climate of the Klamath region is known to be associated with unique microclimates, such as the well-known summer fog zone at Redwood NSP and environs (Barbour and Major 1977). This study suggests that high-elevation riparian areas, which occur above the winter snowline and are irrigated by snowmelt and groundwater flow through the warm, dry summers, sustain a rich pool of cool, temperate species that are, possibly, relicts from a cooler and wetter past. Our findings of divergent patterns in the relationships among elevation, latitude, possibly climate, and diversity in riparian and upland plots suggest riparian plant communities show unique biographic patterns and processes in our park landscapes.

Although the landscape settings of these riparian environments appear to contain a number of short-term stabilizing mechanisms (e.g., late-lying snows, abundant groundwater and soil moisture, and cool microclimates), their long-term vulnerability and viability are poorly understood. A fundamental driver of these systems appears to be winter snowpack, which delays runoff of winter precipitation and allows it to continually recharge groundwater reservoirs and feed perennial streams through the summer, which in turn harbor the rich, predominantly native riparian flora (fig. 5, page 70). Snowpacks in the mountains of northern California and southern Oregon are known to be highly sensitive to temperature, and projected changes in snowpack suggest that in future decades

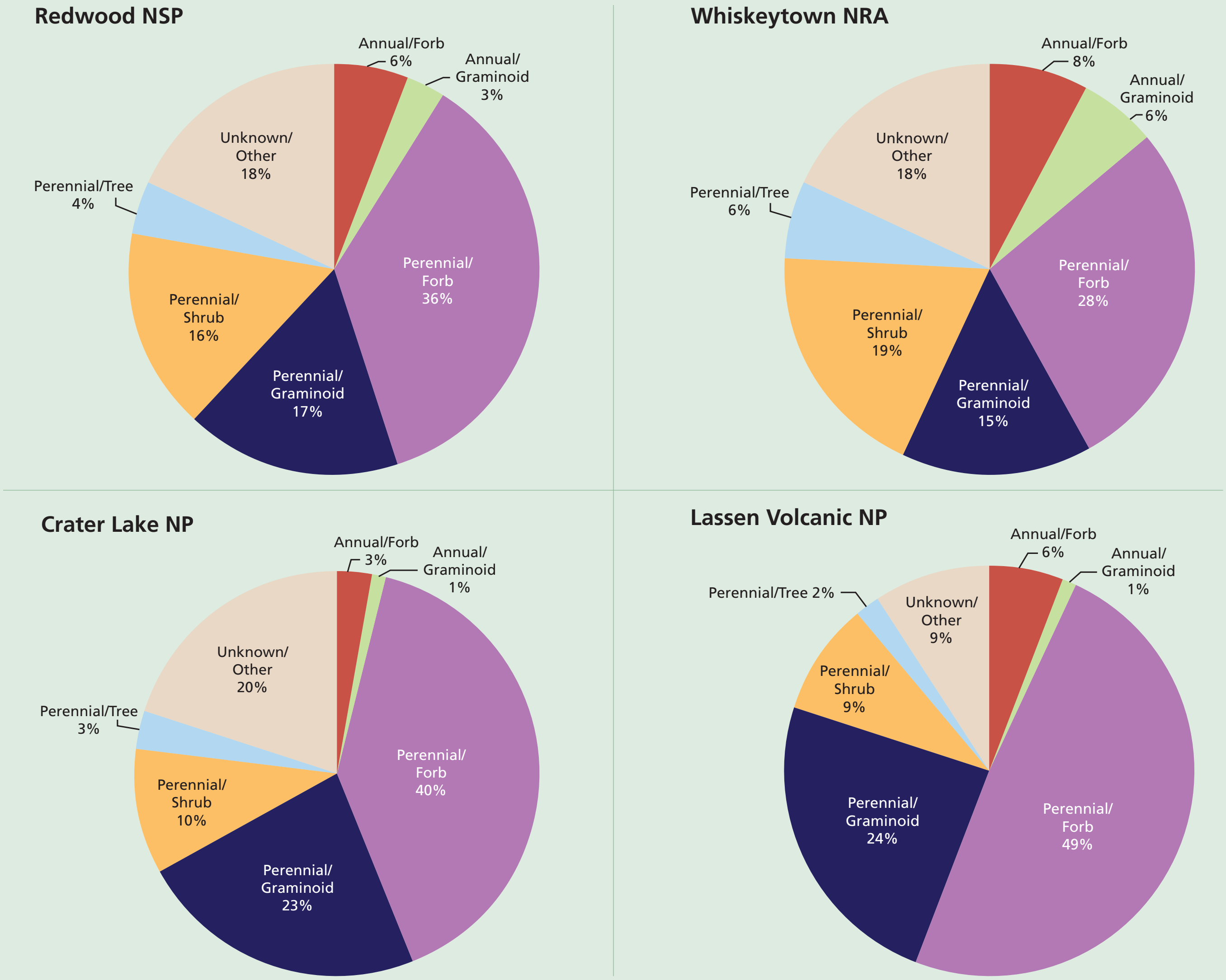

Figure 4. The pie charts show percentages of life history characteristics for all species encountered in riparian plots. Note higher proportions of perennial/forb and perennial/graminoid plant species in Crater Lake and Lassen Volcanic National Parks.

a larger proportion of precipitation may fall as winter rain (Mote 2006), which could impact the hydrological underpinnings of these systems, with unknown consequences for their biodiversity. Inventory, monitoring, and long-term research have the potential to increase our appreciation, understanding, and protection of these globally distinct and hyperdiverse mountain ecosystems in the Klamath Network parks and, potentially, other national park landscapes.

Acknowledgments

This work could not have been accomplished without the diligence and dedication of the Klamath Network vegetation monitoring crews; logistical support from staffs at Crater Lake NP, Lassen Volcanic NP, Redwood NSP, and Whiskeytown NRA; and park scientists who helped us develop the vegetation monitoring program, especially Dennis Odion, Penny Latham, and Sean Mohren. Tom Phillipi provided valuable assistance with R.

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Figure 5. Perennial riparian vegetation grows vigorously immediately adjacent to a stream at Lassen Volcanic National Park. This highly diverse herbaceous community is narrow and, although it is only a small percentage of the 0.1 ha (0.25 acre) plot, contains the bulk of site species richness.

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About the authors

Sean B. Smith *(sean_b_smith@nps.gov) is with the National Park Service, Klamath Network, in Ashland, Oregon.* ***Daniel A. Sarr*** *is a research ecologist with the U.S. Geological Survey's Grand Canyon Monitoring and Research Center in Flagstaff, Arizona.*

PS

Ozone effects on two ecosystem services at Great Smoky Mountains National Park, USA

By Andrew Bingham and Ellen Porter

Abstract

Protected areas such as national parks are recognized as important providers of ecosystem services, the benefits nature conveys to humans. However, some threats to these services, such as air pollution, can derive from outside a park's boundaries. Ground-level ozone (O_3) is a human-made pollutant that at elevated levels can damage vegetation, resulting in decreased growth and increased water loss through evapotranspiration, which in turn results in decreased overall streamflow. Using studies conducted on similar ecosystems in and near Great Smoky Mountains National Park, we estimated the potential loss from O_3 damage of two ecosystem services, climate regulation (through the intermediate service of carbon sequestration) and water provisioning (through streamflow), at this national park. These ecosystem functions directly benefit humans by providing a livable climate and by providing downstream beneficiaries with water for drinking, agriculture, recreation, and hydropower. We found the loss from impairment of these services could be significant when O_3 levels are elevated. A 50% increase in O_3 exposure is projected to result in a loss of carbon (C) sequestration of 500,000–960,000 t C yr^{-1} (metric tons of C per year) (551,000 sh t C yr^{-1}), while a 25% reduction in O_3 concentrations could result in an increase in streamflow of 109.6 M m^3 (million cubic meters) (88,854 ac-ft) from the park during the critical dry August–October period. This highlights the important services provided by protected landscapes such as this national park and the need for more in-depth research on the effects air pollution can have on the benefits we receive from nature.

Key words

air pollution, carbon sequestration, ecosystem services, ozone, water provision

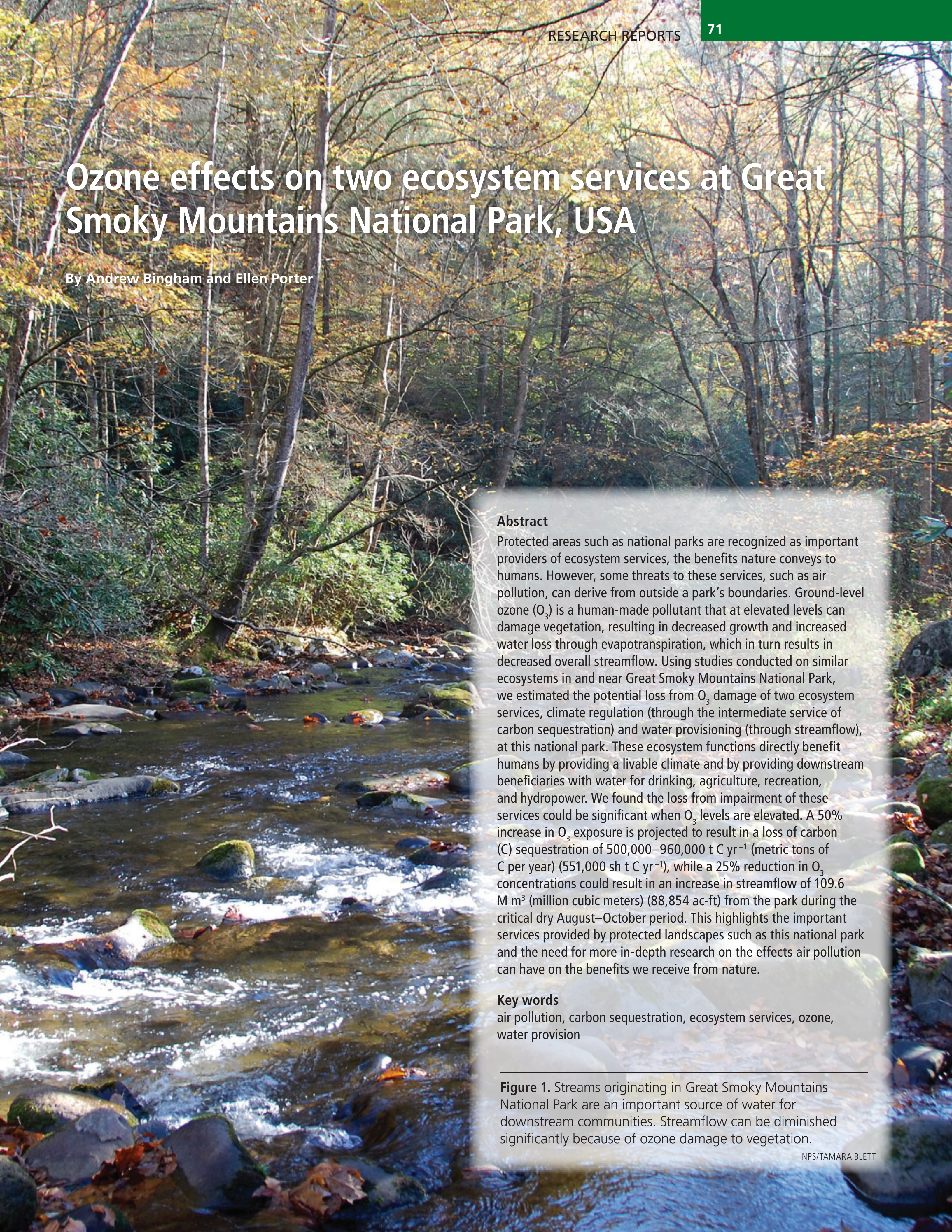


Figure 1. Streams originating in Great Smoky Mountains National Park are an important source of water for downstream communities. Streamflow can be diminished significantly because of ozone damage to vegetation.

NPS/TAMARA BLETT

THE ASSESSMENT OF ECOSYSTEM SERVICES IS IMportant for characterizing the benefits nature provides to humans, and facilitates the use of ecosystem indicators in public decision making (Patterson and Coelho 2009). Ecosystem services have been defined as "components of nature, directly enjoyed, consumed or used to yield human well-being" (USEPA 2013*a*, 3). Some ecosystem services, such as crop pollination and flood protection, are well documented and are fairly straightforward to quantify; others, such as scenic vistas, are less tangible yet no less important to human well-being. As protected areas, the National Park System is ideally situated to provide many services that are beneficial to humans. Traditionally parks have been valued for their aesthetic, spiritual, and cultural contributions to human welfare. Using the ecosystem services framework, however, we now realize that while many services, such as climate regulation or water provision, are directly generated by protected park ecosystems, they flow outside park boundaries and provide significant benefits beyond park borders (fig. 1, previous page). These external contributions are little studied, if at all, but can be crucial sources of services required for human well-being.

Although national parks are among the most protected landscapes in the country, some threats do not respect boundaries. Air pollution may principally originate outside a park but can damage park ecosystems and the services these ecosystems provide if levels are too high. One such pollutant is tropospheric ozone (O_3), which has long been known to damage vegetation and is still considered to be one of the most harmful air pollutants to forests and rural areas (figs. 2 and 3) (Ashmore 2005; Paoletti et al. 2010). It is formed via a complex set of atmospheric reactions in the presence of sunlight as a secondary reaction; generally its precursors are oxidized nitrogen (NOx) and volatile organic compound (VOC) emissions from stationary and mobile sources (Finlayson-Pitts and Pitts 1993). Over the past 20 years there has been a shift in research on the effects of air pollution on forests from a focus on forest health and effects on forest production to a focus on ecosystem services (Paoletti et al. 2010). Much of the focus of air pollution effects on ecosystem services provided by forests has been on changes to intermediate services such as carbon (C) sequestration or nitrogen effects, which can affect climate regulation and biodiversity; however, forest ecosystems are also important sources of other services, including provision of water for human consumption, agricultural and recreational uses, and hydropower production (Compton et al. 2011).

Great Smoky Mountains National Park (hereafter "the park"), incorporating approximately 210,500 ha (520,157 ac), is located in Tennessee and North Carolina. The headwaters for 45 watersheds are located in the park and half of the old-growth forest still present in the eastern United States is located within its boundaries. It has more species of native vascular plants than any other park in North America and more tree species than all of northern Europe (NPS 2002). High levels of tropospheric O_3 have been a concern at the park since the 1970s and can be double those in the nearby cities of Knoxville and Atlanta (NPS 2011). In 2011, O_3 at the park remained at elevated levels associated with demonstrated damage to vegetation (NPS 2013).

NPS/JIM RENFRO (2)

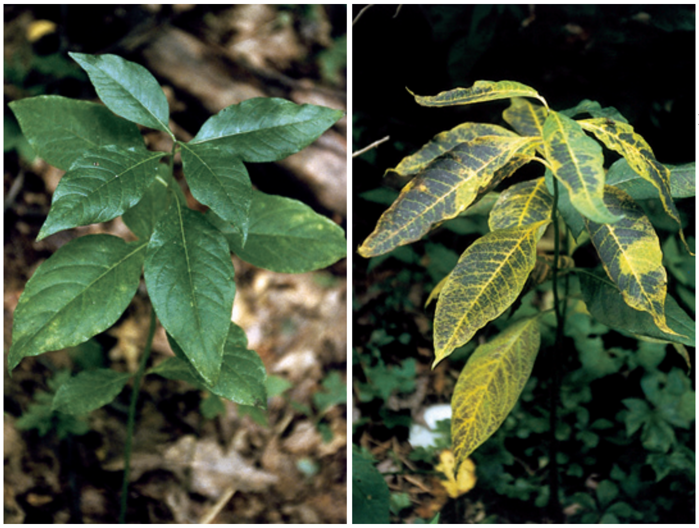
Figure 2. Comparison of healthy black cherry (*Prunus serotine*) leaves on the left and ozone-injured leaves on the right. Black cherry is one of the species planted in the park's ozone garden as a bio-indicator for ground-level ozone.

We examined two ecosystem services: C sequestration and drinking water provision. Carbon sequestration in biomass has been identified as a key strategy for mitigating the effects of climate change caused by anthropogenic additions of carbon dioxide (IPCC 2014). Provision of water for extractive purposes such as municipal, agricultural, and commercial use, and in situ uses such as hydropower production, recreation, and transportation, is a vital benefit provided by ecosystems (Brauman et al. 2007). We used data quantifying changes to tree growth and stream base flow because of O_3 damage to vegetation obtained at a nearby study area to estimate effects on these ecosystem services provided by the park as a whole.

The ecosystem services framework provides an easily understood way for policymakers and nonscientists to conceptualize the important benefits nature provides and to assess the effects external influences can have on protected areas. By translating empirical data concerning effects of air pollution on vegetation to effects on ecosystem services, land managers and policymakers will be able to better incorporate the benefits provided by protected areas in their decisions. Though this approach may not be as robust as direct measurement or modeling, these calculations set the stage and demonstrate the need for further research to better assess the effects of air pollution on ecosystem services.

Carbon sequestration

We used existing data from studies of changes to tree growth because of O_3 exposure to estimate reduction in carbon sequestra-



NPS/JIM RENFRO (2)

Figure 3. Comparison of healthy tall milkweed (*Asclepias exaltata* L.) leaves on the left and ozone-injured leaves on the right. Tall milkweed is distributed widely throughout the park and is especially sensitive to ozone.

NPS/COLLEEN FLANAGAN PRITZ

Figure 4. Forests of the southeastern United States can sequester large amounts of carbon and high ozone levels can reduce tree growth by 40% or more.

tion. Ozone has the effect of reducing carbon storage by reducing the net primary production (NPP) of vegetation (Felzer et al. 2002) (fig. 4). McLaughlin et al. (2007*a*) found that high levels of O_3 can limit the growth of mature forest trees because of chronic alterations in photosynthetic production and carbon allocation, and increased levels of water stress through increased transpiration. Stem increment and sap flow velocity were measured in a variety of tree species over three sites in eastern Tennessee, including the park. McLaughlin et al. (2007*a*) compared responses between two years with average cumulative seasonal O_3 exposure >60 parts per billion (ppb) and one year with elevated O_3 cumulative exposure (50% higher). They found that elevated levels of ambient O_3 exposure were associated with growth reductions of 30–50% (averaging about 40%). Similar reductions in angiosperm biomass were reported by Wittig et al. (2009) for O_3 concentrations above 80 ppb.

Because the McLaughlin et al. study used tree stem increment measurements to obtain changes in rates of growth because of O_3, we used measurements of aboveground net primary production (ANPP) to obtain carbon-budget estimates for southeastern U.S. deciduous forests. Busing (2005) used tree growth increments and relationships between characteristic tree dimensions in the Great Smoky Mountains, Tennessee, to estimate ANPP and found that a range of 630–860 g C m^{-2} yr^{-1} (grams of carbon per square meter per year) (18–25 oz C yd^{-2} yr^{-1}) is accumulated in old stands of temperate deciduous forest similar to those found in the park (table 1). We also used results from two modeling studies to

Table 1. Range of carbon sequestration losses with 40% reduction in aboveground net primary production

Study	ANPPg C m^{-2} yr^{-1}	GRSM t yr^{-1}	Is 40% of (t)	Difference (t)	Equal to Cars yr^{-1}
Busing (2005)	860	1,437,760	2,396,266	958,506	688,686
Curtis et al. (2002)	446	745,629	1,242,714	497,085	357,156

GRSM = Great Smoky Mountains National Park
Deciduous acreage in Great Smoky Mountains National Park (m^2): 1.67 billion
Average car emissions yr^{-1} (t C): 1.4

inform our range of ANPP. Curtis et al. (2002) used biometric as well as eddy covariance methods to estimate NPP for several sites. The eastern Tennessee deciduous forest site in this study had an estimated ANPP of 446 g C m^{-2} yr^{-1} (13 oz C yd^{-2} yr^{-1}) (wood + leaves portion of their NPP estimate). Zhang et al. (2007) used the Dynamic Land Ecosystem Model to estimate carbon storage in the park. Their results revealed an NPP contribution of 748 g C m^{-2} yr^{-1} (22 oz C yd^{-2} yr^{-1}). They assumed a belowground-to-aboveground NPP ratio of 0.4, which resulted in an estimated ANPP of 449 g C m^{-2} yr^{-1} (13 oz C yd^{-2} yr^{-1}).

Based on these studies of C accumulation in eastern Tennessee deciduous forests, we examined a range of ANPP values, using the value of 446 g C m^{-2} yr^{-1} (13 oz C yd^{-2} yr^{-1}) as a lower bound and 860 g C m^{-2} yr^{-1} (25 oz C yd^{-2} yr^{-1}) as an upper bound for estimates of C sequestration in the park. Deciduous forest in the park comprises an area of 167,181 ha (413,114 ac). Under the assumption that all deciduous forest adds biomass at the same rate, we estimate from the ANPP values that 0.7–1.4 M t C yr^{-1} (million metric tons of carbon per year) (0.8–1.5 M short tons [sh t] C yr^{-1}) is added as biomass to the aboveground vegetation in the park. Under conditions of elevated cumulative O_3 exposure, these ANPP values would represent a 40% reduction in growth according to McLaughlin et al.'s observations. Therefore, carbon sequestration without O_3 damage could be about 1.2–2.4 M t C yr^{-1} (1.3–2.6 M sh t C yr^{-1}). The difference from the current level of C sequestration, and consequently the lost C sequestration in the park deciduous forest in a year with 50% above average O_3 exposure, could be in the range of 500,000–960,000 t C yr^{-1} (551,000–1,057,920 sh t C yr^{-1}) because of the growth effects of O_3 damage.

Carbon sequestration discussion

Damage to vegetation from enhanced levels of O_3 has been documented in Great Smoky Mountains National Park (Neufeld et al. 1991; Chappelka et al. 1999, 2007) and results in lowered amounts of biomass accumulation (McLaughlin et al. 2007*b*) (see figs. 2 and 3). Our climate has unequivocally been shown to be warming because of observed increases in anthropogenic greenhouse gases, especially carbon dioxide (CO_2) from fossil fuel burning (IPCC 2013). Trees can act as a sink for CO_2 by fixing carbon during photosynthesis and storing excess carbon as biomass (Nowak and Crane 2002) and can store large amounts of carbon for long time periods (Heath et al. 2003). About 20% of the world's plant biomass can be found in temperate forests such as those found in the park, and mature temperate forests have high rates of C sequestration (Bonan 2008). Ozone can act to reduce carbon storage by reducing net primary production, and on a worldwide scale has been found to account for a reduction of carbon storage of about 800–1,300 M t C yr^{-1} (882–1,433 M sh t C yr^{-1}) (Felzer et al. 2005).

The southeastern United States has been identified as an especially important region for C sequestration because it is an area where high O_3 levels coincide with high plant productivity (Felzer et al. 2005). Applying the growth reduction estimate of ~40% in deciduous forest found by McLaughlin et al. (2007*b*) to the ANPP estimates of biomass accumulation, we find that approximately 500,000–960,000 t C yr^{-1} (551,000–1,057,920 sh t C yr^{-1}) of C sequestration can be lost during a year with high cumulative O_3 exposure. To put this in context, according to the U.S. Environmental Protection Agency, the average vehicle in the United States emitted 5.1 t (metric tons) (5.6 sh t) of CO_2 in 2007 (USEPA 2012). Using this figure, the amount of lost C sequestration is similar to the amount of carbon emitted by about 360,000 to 690,000 vehicles per year.

Our analytical approach documents an effective method for translating growth reductions because of O_3 damage to effects on ecosystem services, and finds that in an anomalously high year of O_3 exposure, when cumulative O_3 exposure exceeds the average by 50% and hourly maximum values reach 120 ppb, significant losses of C sequestration can occur. While this is a relatively uncommon level, the park has experienced elevated levels of O_3 as recently as 2012 (National Park Service, B. Sive, atmospheric chemist, personal communication, Lakewood, Colorado, 29 May 2014), and the large amount of lost C sequestration at this exposure suggests that even at lower O_3 levels there is likely to be a substantial loss of C sequestration capacity. A meta-analysis by Wittig et al. (2009) found growth reductions of 11–17% at an elevated O_3 exposure average of 97 ppb. Even at average background O_3 levels of 40 ppb across the 263 studies, researchers found a reduction in tree biomass of 7%. These widely documented reductions in photosynthetic capacity and plant growth suggest that even with a large amount of uncertainty there is likely to be a substantial negative effect on C sequestration at more typical O_3 levels (USEPA 2013*b*).

Water provisioning

We also examined how previous study results could be employed to obtain estimates of changes to water provision

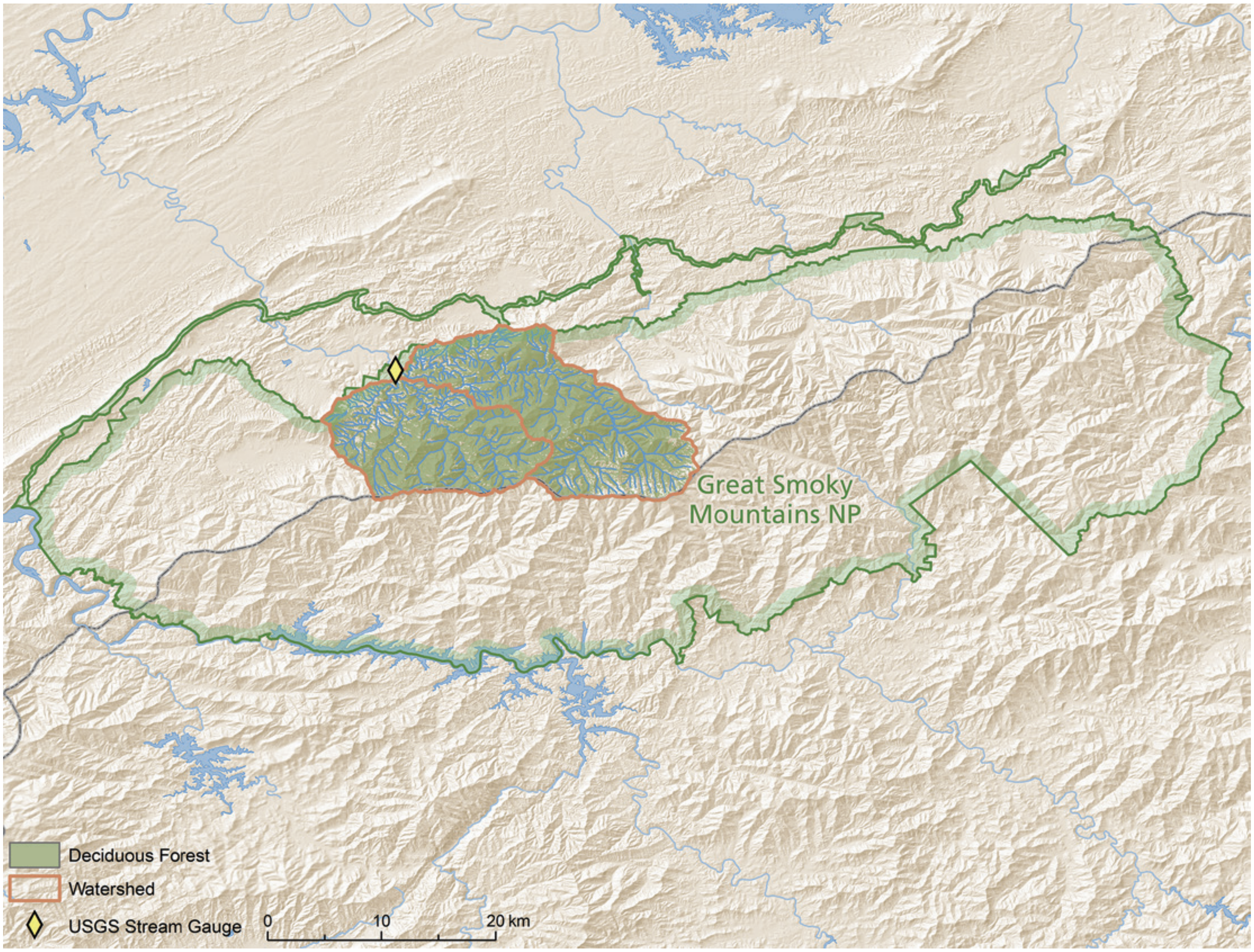


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Figure 5. Deciduous area in the two watersheds in Great Smoky Mountains NP used to estimate reductions of base flow. Base flow from deciduous areas can be reduced by as much as 62% during August–October because of ozone injury to foliage.

because of O_3 damage to vegetation. High levels of O_3 exposure, especially acute exposure at high concentrations, have been found to have several harmful effects on vegetation, including the onset of sluggish stomatal responses to stimuli (McLaughlin et al. 2007*b*) (see figs. 2 and 3). This can lead to incomplete closure of the stomata, weakening control of water loss that can persist long after O_3 exposure, and may lead to increased evaporation of water from leaves as the stomata fail to close (McLaughlin et al. 2007*b*; Paoletti 2007). This increased water use and loss through the leaves causes reduced soil moisture and reductions in streamflow in the watershed as trees increase their uptake of water to offset the loss. Using a stepwise regression model, McLaughlin et al. (2007*b*) predicted that a 25% reduction in O_3 would increase watershed base flow by 62% during the dry August–October period and would result in a long-term annual average increase in streamflow of around 5%, as less soil water would be lost through vegetation.

We evaluated the potential consequences of an O_3-induced decrease in streamflow on an area of the park. The U.S. Geological Survey (USGS) stream gauge 03497300 is located near the park boundary and records outflow from a drainage area of approximately 27,500 ha (67,954 ac) (USGS 2012), nearly all of which is located within two watersheds in the park (fig. 5). Mean annual volume of water passing this gauge for the period 1964–2010 is 251 million m^3, which is more than 66 billion gallons, or 203,488 ac-ft. During the August–October period the mean total flow passing the gauge is 30,866,988 m^3 (25,024 ac-ft) (table 2). McLaughlin et al. (2007*a*) estimated that during this period 95% of the streamflow (29,323,638 m^3 or 23,773 ac-ft) comprises base flow. Using ESRI's ArcGIS 10.1 software and the USGS 2006 National Land Cover Database (NLCD), we have calculated that deciduous forest occupies an area of approximately 24,000 ha (59,305 ac) of the 27,500 ha (ArcGIS NLCD value; 67,954 ac) of the two watersheds that drain past this stream gauge, or about 88% of the land area.

Table 2. Streamflow at USGS gauge 03497300, Little River, above Townsend, Tennessee

Month	Mean CFS	Seconds mo^{-1}	M^3 mo^{-1}
August	162	2,678,400	12,288,071
September	126	2,592,000	9,249,085
October	123	2,678,400	9,329,831
August–October			30,866,987

Note: CFS = cubic feet per second

We assumed an even distribution of precipitation across these two watersheds during the 1964–2010 period from which the stream gauge average is computed. Since the McLaughlin et al. (2007*a*) study examined base flow effects in deciduous forests, we calculated that approximately 25.7 M m^3 (20.8 M ac-ft) (88%) of base flow would originate in deciduous forest areas of the two watersheds during the August–October period when O_3 exposure is at average levels. McLaughlin et al. (2007*a*) predicted that if O_3 were decreased 25% from average-year concentrations, an increase in streamflow of 62% could occur; this would increase flow to 41.5 M m^3 (33.6 M ac-ft) at the stream gauge. The difference, meaning the missed base flow as a result of O_3 damage to vegetation, is about 15.8 M m^3 (12.8 M ac-ft) over these two watersheds (table 3). Over the entire park area (1,671,813,900 m^2; 167,814 ha [413,114 ac] of deciduous forest according to NLCD) this would indicate a lost base flow of 109.6 M m^3 (88,854 ac-ft) over the August–October period.

Water provisioning discussion

Provisioning of water is one of the most important services ecosystems provide to humans (Brauman et al. 2007), and high O_3 exposure may indirectly threaten water delivery from Great Smoky Mountains National Park. Forest ecosystems are the most important source of water in the United States, providing 53% of the nation's water supply and about 62% of the water supply in North Carolina and Tennessee (Brown et al. 2008). Climate change may exacerbate stress on water resources because of increased precipitation variability, and it may change seasonal timing of runoff (IPCC 2013). This could act to intensify changes in streamflow from O_3, as the cumulative seasonal effects of O_3 exposure on base flow are expected to have the greatest impact during the late-season low-flow period (McLaughlin et al. 2007*b*). Base flow is one aspect of the flow regime that is critical for regulating biotic production and diversity, and reductions are expected to have effects on in-stream nutrient concentrations, water temperatures, and dissolved oxygen levels (Baron et al. 2002; McLaughlin et al. 2007*b*; Baron et al. 2013).

In addition to ecological consequences, streamflow originating in the park is appropriated for human uses downstream. Many rivers and streams originating in the park drain into impoundments where the water is used for agriculture, recreation, and hydropower. Much of eastern Tennessee relies on both groundwater and surface water as sources of drinking water. Maryville, for example, a city of 27,000, relies on the Little River (approximately 30 km [19 mi] downstream from the USGS gauge used in this analysis) for its drinking water. Some of these cities, including Maryville, have identified drought as a potential threat, even implementing mandatory water restrictions in the past (Tennessee Department of Environment and Conservation 2009).

By applying McLaughlin et al.'s (2007*a*) findings of a 62% reduction of stream base flow during the crucial dry August–October period, we find that 109.6 M m^3 (88,854 ac-ft) of lost base flow is possible over the entire park because of damage to vegetation when O_3 levels are elevated by 25%. Alcoa, Tennessee, is downstream from the Little River USGS gauge and draws its water from the Little River (City of Alcoa 2007). An average resident uses approximately 73.3 m^3 mo^{-1} (19,364 gal/month) of water (City of Alcoa 2007). The amount of stream base flow reduction because of O_3 damage to vegetation in the park is approximately equal to the amount of water used by 498,000 residents of Alcoa during an average three-month period. A subsequent study found similar reductions in streamflow in high O_3 years over a wide geographic area of the southern Appalachian Mountains consisting of many tree species (Sun et al. 2012). This indicates that O_3 could be an important influence on streamflow and ecosystem services over a large area, and could act to exacerbate drought conditions.

Table 3. Base flow reduction due to ozone-damaged vegetation

Parameter	Volume (m^3)	Comparison	Metric
August–October streamflow	30,866,987		
August–October base flow	29,323,638		
Base flow originating in deciduous in-stream gauged watersheds	25,707,169		
Deciduous base flow (m^3) per m^2 in gauged watersheds	0.11	Alcoa resident average water usage	73.3 m^3 mo^{-1}
62% of base flow originating in deciduous watersheds	41,463,175		
Difference between measured deciduous base flow and 100%	15,756,006	Equivalent Alcoa residential customers	71,629
Deciduous base flow in GRSM	178,751,369		
62% of deciduous base flow in GRSM	288,318,357		
Difference between measured deciduous GRSM base flow and 100%	109,566,988	Equivalent Alcoa residential customers	498,106

Conclusions

As permanently protected areas, national parks are important providers of ecosystem services that benefit humans in multiple ways. However, threats to these services often come from outside the park's borders and are beyond the control of the National Park Service. The benefits from nature preserved in national parks can be great, yet decision makers often lack information on how people benefit from specific ecosystem services (Turner and Daily 2008; Compton et al. 2011). Resource preservation and protection are often overlooked policy objectives, yet these objectives can be justified powerfully by consideration of ecosystem services and the benefits they provide (Salzman et al. 2001). This is especially true for O_3, as the long-range transport of O_3 can result in elevated levels in rural protected areas far from emissions sources (Adams et al. 1986).

Although this analysis entails a greater level of uncertainty in results because of the limited number of studies used to estimate the effects on changes to ANPP and especially stream base flow (and assumptions about the transfer of effects to the ecosystem scale), it nonetheless demonstrates a fast, straightforward, and easily comprehensible method for determining effects on ecosystem services. We found that injury to vegetation when O_3 levels are 50% above normal is projected to decrease carbon sequestration across the park by 500,000–960,000 t C yr^{-1} (551,000–1,057,920 sh t C yr^{-1}), the amount of carbon added to the atmosphere by 360,000–690,000 cars in a year. In addition we found that reducing O_3 levels by 25% could increase streamflow originating in the park by 109.6 M m^3 (88,854 ac-ft) during the dry August–October period. This is the equivalent water use of approximately 500,000 municipal consumers at a time when water demand by both humans and ecosystems is often at its peak but supplies are often reduced.

The potential magnitude of losses draws attention to the urgent need for further investigation and more rigorous estimates of loss of ecosystem services and human well-being that is incurred from continued O_3 pollution. Connecting the environmental consequences of air pollution (effects on tree growth, water loss, and streamflow) to the human beneficiaries of these services is a crucial link, especially since intermediate ecosystem services such as C sequestration are often underappreciated components of final ecosystem services (USEPA 2013*a*). Framing this link in a manner that is accessible to policymakers, such as putting it in terms of automobile emissions or municipal water customers, is an important step toward communicating the damage suffered by ecosystem services from O_3 incursion and the benefits of implementing mitigation measures.

Managing ecosystem services will become increasingly important as the human footprint on the landscape continues to grow (Kreman 2005). Raising the awareness of policymakers about how their decisions affect how humans can benefit from nature, even when these benefits originate in otherwise protected areas such as national parks, is crucial to their preservation and the human well-being associated with those services. Quantifying the deleterious effects of O_3 pollution on ecosystem services and putting them in a framework that can easily be understood and used to guide policy decisions are an important component of pollution mitigation strategies.

We now realize that while many [ecosystem] services . . . are directly generated by protected park ecosystems, they flow outside park boundaries and provide significant benefits beyond park borders. These external contributions are little studied, if at all, but can be crucial sources of services required for human well-being.

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About the Authors

Andrew Bingham *(drew_bingham@nps.gov) is an ecologist with the NPS Air Resources Division.* ***Ellen Porter****, biologist, recently retired from the NPS Air Resources Division.*

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