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PARKScience

Integrating Research and Resource Management in the National Parks

National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science
Office of Education and Outreach

MILESTONES IN SCIENCE AND NATURAL RESOURCE MANAGEMENT: 1916–2016

Our timeline explores the evolving roles of park science expressed through key events, people, and policies that shaped our first century of natural resource stewardship in the national parks

Also in this issue

- Shifts in vegetation projected under changing climate at Hawai`i Volcanoes
- Thirty-year study of leafcutter ant populations at Organ Pipe Cactus
- Mine tailings reclamation improves water quality in Yellowstone creek
- A vulnerability assessment tool for karst habitats at C&O Canal
- Experimental reintroduction of beach pea at Indiana Dunes

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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. 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 subject-matter experts review content for clarity, completeness, usefulness, scientific and technical soundness, and relevance to NPS policy.

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

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From the Editor

Making history for the parks

WE HIGHLIGHT NPS USE OF SCIENCE AND THE EVOLUTION OF science-based natural resource management from 1916 to 2016 in a pullout timeline that you will find near the middle of this issue. With this timeline we share insights into the evolution of science as a tool for understanding and managing the resources entrusted to our care. My perspective is that while progress over the last century was uneven, in the last roughly 35 years we have experienced a surge in the use and refinement of scientific tools and processes that aid us in our work, and because of this we are better able to protect the natural resource values of our parks so that people may more fully experience them.

With this issue I too am marking a personal milestone in my career with the National Park Service. I will be retiring at the end of March, and this will be my last issue as editor of *Park Science*. Since 1994 it has been my professional privilege and personal pleasure to serve as your editor. The idea that national parks are as ecologically undisturbed as any areas in the world intrigued me in my early twenties. I wanted to work for the National Park Service and learn all I could about the parks. *Park Science* has been all I imagined in this way and more—a chance to think and write about our parks and help others present their work in the best possible manner, to better appreciate the scientific method for all its possible applications, and to feast on publication design considerations to advance science communication for the National Park Service. It truly was a right brain–left brain experience and I have loved it. Each issue was like climbing a mountain, my favorite activity in the national parks when I was an interpretive park ranger earlier in my career. Both endeavors require planning and commitment, critical thinking, the ability to deal with performance anxiety, and fostering a team experience in the execution. Afterward there's often a huge sense of satisfaction, and then we climb again. Also I am motivated by the power of putting ideas in print. Articles in *Park Science* join an important body of literature, so it is important to put them together carefully and thoughtfully for the impact they can have now and in the future. To make this contribution to park stewardship has been immensely satisfying.

I will miss the intellectual challenges, creativity, and collaborations of this work, but I am confident *Park Science* will go on in great fashion. The immediate goal of the Natural Resource Stewardship and Science Directorate is to conduct a review of the journal and develop a strategic plan to guide the publication into the future, and the process to hire a new editor has already begun. You can expect to find periodic updates on the transition on the *Park Science* website.

Park Science is a superior vehicle for the transfer of knowledge about how research supports management of our parks. This purpose is as relevant today as when the journal began in 1980 and is the main reason for its continued success. Readers, authors, NPS managers and park staffs, international partners, cooperators, contractors, coworkers, and even members of the public have regularly expressed their enthusiasm, support, and encouragement to me for *Park Science*. Thank you.

As professional resource managers and researchers we deal with change on a daily basis. We are fortunate to have a mission in the National Park Service that is wonderfully utilitarian. Our contributions to this mission are especially important to making a history for the parks that we can all be proud of. In doing our part each day we strengthen the scientific traditions and values that undergird good park management. Carry on.

—Jeff Selleck, Editor

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ON THE COVER

Montane wet habitat of Hawai`i Volcanoes National Park is forecast to become warm and dry by the end of the 21st century. Over time most of the species pictured here are projected to occur outside of current intensely managed Special Ecological Areas, focal sites for managing rare and endangered plants.

HAWAI`I VOLCANOES NATIONAL PARK/MARK WASSER

ONE TAM/RACHEL KESEL

JOHN TUDEK

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UPCOMING TRANSITION

Editor Jeff Selleck is retiring in March 2018. *Park Science* is an important asset to the National Park Service and will be retained. To make the transition to a new editor, *Park Science* will be undergoing a review and development of a strategic plan to guide the publication into the future. The process is expected to take many months. Please check the website for periodic updates or contact the interim publication manager, Dave Anderson, at Park_Science@nps.gov or 970-225-3539 for further information.

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CASE STUDIES

LITERATURE REVIEW

Letter

Dear *Park Science* Editor,

TWO YEARS AGO OUR ARTICLE, "NEARSHORE CONDITIONS in the Great Lakes national parks: A baseline water quality and toxicological assessment" was published in the *Park Science* 2015–2016 Winter edition (volume 32, number 2). In this piece we presented a summary of nearshore conditions in five Great Lakes coastal park units and related our results to interim water quality criteria identified by the Environmental Protection Agency for dissolved oxygen, chlorophyll *a*, dissolved inorganic nitrogen, dissolved inorganic phosphorus, and water clarity (table 2 in the publication). In addition, we assessed sediment quality based on regional and national ecological criteria. We noted that based on the water criteria, conditions at National Park Service (NPS) sites were rated "good" for each of these parameters and sediment quality was generally within published thresholds for ecological health.

Shortly after our publication, the EPA published a broader report summarizing results from the 2010 National Coastal Condition Assessment (NCCA; EPA 2015), and presented water and sediment quality criteria specific to Great Lakes coastal waters. The new water criteria addressed total phosphorus, chlorophyll *a*, water clarity as Secchi depth, and bottom dissolved oxygen. Based on the new water criteria, all of the NPS sites received "good" ratings for bottom dissolved oxygen, and a majority of NPS sites received "good" ratings for total phosphorus and chlorophyll *a* (figs. 1 and 2). However, far fewer NPS sites received "good" ratings for water clarity; in fact all sites at Pictured Rocks and Indiana Dunes and a majority of sites at Apostle Islands and Sleeping Bear Dunes received "fair" or "poor" ratings for water clarity. Such low ratings, often in park waters prized for their water clarity, may indicate emerging water clarity concerns in these parks, but may also reflect weather or hydrodynamic conditions at the time of sampling, site locations in more turbid coastal embayments, or other factors. It is worth noting that a majority of NPS sites still received an overall Water Quality Index rating of "good," and no NPS sites received an overall Water Quality Index rating of "poor."

The thresholds for ecological quality associated with the new sediment quality index (sediment toxicity and sediment contaminants) did not change following the 2010 NCCA report (EPA 2015). However, one aspect of sediment quality not evaluated in our original article was the Oligochaete Trophic Index, an indicator of organic enrichment in the sediments. Less than half of the NPS sites sampled for sediment quality had oligochaetes present, and although several sites were rated "poor" or "fair" for organic enrichment based on the Oligochaete Trophic Index, these results did not correlate strongly with the measured percentage of total organic carbon in the sediments, making them difficult to interpret. Finally, fish tissue contaminant burdens were assessed in the EPA (2015) report against the whole-body tissue concentrations for lowest observed adverse effects level. Our previous article assessed fish tissue concentrations against the more stringent criteria for human health used by Canada and the United States under the Great Lakes Water Quality Agreement General Objective 9. While there is no widespread exceedance of human health criteria, legacy contaminants continue to be measured in the majority of fish tissues.

Overall, this analysis provides a more nuanced view of water quality conditions in Great Lakes national parks and suggests that several parks would benefit from additional monitoring and assessment related to water clarity—particularly in light of recent broad-scale changes in water clarity throughout the Great Lakes region (Yousef et al. 2017). Complete results from the 2010 National Coastal Condition Assessment, including sites within NPS units and the broader Great Lakes region, are accessible at https://www.epa.gov/national-aquatic-resource-surveys/national-coastal-condition-assessment-2010-results.

References

US Environmental Protection Agency (EPA). Office of Water and Office of Research and Development. December 2015. National Coastal Condition Assessment 2010. EPA 841-R-15-006. Washington, DC, USA. http://www.epa.gov/national-aquatic-resource-surveys/ncca.

Yousef, F., R. Shuchman, M. Sayers, G. Fahnenstiel, and A. Henareh. 2017. Water clarity of the Upper Great Lakes: Tracking changes between 1998–2012. Journal of Great Lakes Research 43(2):239–247.

Sincerely,

Brenda Moraska LaFrancois, William O. Hobbs, and Eva DiDonato

Technical Note

New herbarium label in the Interior Collections Management System for NPS botany collections

By Wendy Weckesser

FOR ANY RESOURCE MANAGER WITH PLANT COLLECTIONS to curate, an updated version of the herbarium label template is now available in the Interior Collections Management System (ICMS), the software used to catalog NPS museum collections. As stated in 36 CFR 2.5, Research Specimens, "specimens from national parks placed in museum collections are required to bear official NPS museum labels." While working as botanist at Amistad National Recreation Area, Texas, I curated more than 1,600 plant collections using ICMS. Although the label template for herbarium collections (NPS Form 10-512) in ICMS meets NPS standards for museum curation, it does not include adequate information for a standard herbarium label (fig. 1). The ICMS template lacks the name of the collection (for example, "Flora of Amistad National Recreation Area"), the state and county where the collection was made, space for a specimen description, and the collector's collection number.

The museum catalog data necessary for a complete herbarium label are recorded in ICMS, so it simply became a matter of reconfiguring the template to serve as both museum and herbarium label. In collaboration with the NPS Museum Management Program and the ICMS vendor Re:discovery Software, Inc., we have modified NPS Form 10-512 to greatly improve its usefulness as an herbarium label. All the pertinent botanical data, as well as the NPS curatorial data, are incorporated into the label template (fig. 2).

The revised label still has some limitations, however. The scientific name is not in italics and the number of characters is limited in the fields for scientific name and specimen description. Wording for the specimen description must be succinct. Though there is room for further improvement, this version of the herbarium label template should prove useful to National Park Service botanists and museum curators who use the ICMS.

For more information on accessing the template, contact technical support at Re:discovery Software, Inc. (e-mail: support@rediscov.com).

Acknowledgments

The author wishes to thank the collaborators from the NPS Museum Management Program and Re:discovery Software, Inc., for their contributions to the label update and this article. Comments from reviewer Steve Buckley, Lassen Volcanic National Park, improved the overall quality of the article and are greatly appreciated.

About the author

Wendy Weckesser was a biological science technician at Amistad National Recreation Area, Texas. She can be reached at wendyweck13@gmail.com. Thanks also go to Jack Johnson, Amistad National Recreation Area, for the herbarium sheet specimen photograph.

NATIONAL PARK SERVICE NPS FORM 10-512 (June 1982)

Park Code AMIS

Technical Name Leucaina retusa Benth. Cat. No. 60688

Common Name golden ball leadtree Acc. No. 00312

Locality Pecos River, Weir Dam off Hwy 90 Elevation

Habitat Bank of Pecos River at base of limestone cliff, dense tree and shrub vegetation

Collected By W. Weckesser Date 4/22/2014

HERBARIUM COLLECTION

Figure 1. The original herbarium label template, Form NPS 10-512. The template lacks the name of the collection, state and county, specimen description, and collector number.

FLORA OF AMISTAD NATIONAL RECREATION AREA

County and State: Val Verde, TX

Scientific Name: Leucaina retusa Benth.
Family: Fabaceae Park Code: AMIS
Common Name: golden ball leadtree Cat. #: 60688
Acc. #: 00312

Locality: Pecos River, Weir Dam off Hwy 90
Elevation: UTM Z/E/N:14/264059/3299383

Habitat : Bank of Pecos River at base of limestone cliff, dense tree and shrub vegetation

Description: Tree, leaflets elliptical, base asymmetrical, flower head globose to 2 cm diam, flowers yellow.

Collector & Collection Number: W. Weckesser 1682
Collection Date: 4/22/2014

National Park Service Form 10-512 (Herbarium Collection)

Figure 2. The modified herbarium label template, Form NPS 10-512. The modified format includes all pertinent botanical data as well as the required NPS museum accession data.

PS

Tributes

Gary L. Larson, Limnologist

By Sam Brenkman[1], Bob Hoffman[2], Bob Hughes[3], Barbara Samora[1], and Angela Strecker[4]

DR. GARY LARSON DIED SUDDENLY on 3 October 2017 of cardiac arrest. This came as a shock to all of us who knew Gary as a big guy with a big smile and laugh, who was also an especially enthusiastic walker. Gary received his BSc in Fisheries (1966) and MSc in Limnology (1969) from the University of Washington, and his PhD in Zoology (1972) from the University of British Columbia. His research passion beginning in those years was montane limnology, particularly zooplankton ecology and the behavioral ecology of freshwater fish and amphibians. Gary began his postgraduate career as a research professor at Oregon State University (OSU) focusing on the toxicology of chloramines on crayfish. He then worked for the National Park Service in Great Smoky Mountains National Park (1977–1981) as an aquatic ecologist, and in the Midwest Regional Office (1981–1984) as regional chief scientist. During and following that period, Gary published several insightful articles documenting the displacement of native brook trout by nonnative rainbow trout in small Appalachian streams. In recognition of his contributions, he received an Honor Award for Superior Service from the US Department of the Interior in 1981. But Gary's love of the Pacific Northwest brought him back to Oregon, where he was a research aquatic ecologist in the NPS Cooperative Park Studies Unit at OSU (1984–1993) and the US Geological Survey (USGS) Forest and Rangeland Ecosystem Science Center (FRESC; 1993–1996) in Corvallis, Oregon. From 1997 until his government retirement in 2006, Gary was a FRESC research manager, and also a FRESC acting codirector in 2003. He was a USGS scientist emeritus until 2016.

1 National Park Service
2 US Geological Survey, retired
3 Amnis Opes Institute
4 Portland State University

While in Oregon, Gary led two groundbreaking research programs. The first was the long-term monitoring and assessment of the water quality and ecology of Crater Lake (Crater Lake National Park; 1982–2007), which led to the publication of two special journal issues: *Lake and Reservoir Management* (1996) and *Hydrobiologia* (2007), in which Gary was senior or junior author of 16 articles covering topics ranging from water quality to fish ecology. Those studies documented the results of 10 and 20 years, respectively, of monitoring Crater Lake natural processes and effects on lake water clarity. Those long-term studies resulted from Gary's impressive knack for leveraging limited funds and others' scientific curiosity into a major systematic investigation. In recognition of his many contributions, Gary received the Pacific Northwest Regional Office Appreciation Award for Outstanding Assistance to Crater Lake National Park in 1987, the Research Scientist of the Year Award from the National Park Service in 1995, and the Superior Service Award from the National Park Service in 2006. He also received Star Monetary Awards from the USGS in 2003, 2004, and 2005.

The second research program centered on the ecological effects of introduced trout in national park lakes. That research incorporated a program review by independent scientists and generated 11 journal publications documenting the multiple negative effects of nonnative trout on lake food webs and amphibian behaviors. At Mount Rainier National Park, Gary worked with park staff for more than two decades to collect the first data set describing basic ecological conditions of park lakes that serve as an important benchmark for tracking long-term change in the park. Through these studies he also assisted the park in developing specific management actions to restore natural lake conditions. Gary was also involved in proposing and motivating aquatic research in North Cascades National Park, and worked closely with the staff of the National Park Service's North Coast and Cascades Inventory and

COURTESY OF MARIA LARSON MARX

Gary L. Larson

Monitoring Network and Klamath Network in supporting and participating in the development of their montane lake inventory and monitoring protocols and programs.

From the 1980s to 2000s, Gary provided key research and management contributions to the fisheries and aquatic programs at Olympic National Park. In 1987, Gary led some of the first limnological studies of mountain lakes in the park. In 1996, he assembled a scientific panel and coauthored a comprehensive report that was a catalyst for additional monitoring and management of Lake Ozette sockeye salmon. His efforts ultimately contributed key information to the federal listing of Ozette sockeye as a threatened species. In 2002, Gary assembled and chaired a panel of experts to address the status of Lake Crescent trout populations. The recommendations from the expert panel to the park superintendent led to key changes in fisheries management of the lake and generated future monitoring and research. Gary also worked with park staff to coauthor a journal article on federally threatened Lake Cushman bull trout.

As indicated by his publication productivity and awards, Gary was one of the few scientists who could both serve as an upper-level manager in a federal science center and publish consistently. As a thoughtful research manager, Gary helped guide FRESC through some difficult times and make the science center one of the most productive in the USGS. Gary was a caring, supportive, and enthusiastic mentor to many graduate stu-

CONTINUED FROM PAGE 7

dents and young professionals who went on to develop successful research and management careers in natural resources science at local, regional, and national levels. In the context of these accomplishments, Gary's focus was always to better understand and protect the natural world and the resources he deeply cherished.

After retiring from FRESC, Gary was keen to stay active in the field of limnology. Gary served on the board of directors of the Oregon Lakes Association and the advisory board of the Center for Lakes and Reservoirs at Portland State University. Ever the researcher, one of his retirement projects was compiling a large database of zooplankton assemblage compositions in mountain lakes of the USA and Canada, largely from unpublished paper reports. Ultimately, with Gary's persistence and infectious love of limnology, the database grew to include over 1,200 lakes that covered almost 30 degrees of latitude. A collaborative publication that employed this important data set is currently in revision.

But Gary was much more than a highly productive scientist; his greatest love was reserved for his wife Ingrid, his two daughters and sons-in law Andrea (Jon) and Maria (Chris), and his four grandchildren, Torbin, Tobias, Solveig, and Rasmus. Gary also enjoyed music and folk dancing, the warm camaraderie of friends and colleagues, the conviviality of sharing good food and good wine (especially Ingrid's home-cooked meals), enthusiastic and meaningful conversation, good jokes and laughter, and sharing in the adventures of the people who populated the landscape of his life. In addition to the challenges of limnological research, Gary delighted in self-remodeling his home and restoring a Model-A Ford. No matter what Gary did, he always did it with generosity and great enthusiasm. His journey was one of awareness and understanding of the natural world that he explored and studied, and of the people who traveled with him on his path of discovery. PS

Legacy of NPS historian Richard Sellars lives on in science-based park management programs

By the editor

THE NATIONAL PARK SERVICE and its huge family of partners, supporters, fans, and alumni lost an important and influential figure on 1 November 2017 in the death of Richard West Sellars, NPS historian, author, lecturer, and courageous student of NPS policy archives. He lived in Santa Fe, New Mexico, and was 81 years old.


COURTESY OF DWIGHT PITCAITHLEY

Richard West Sellars

Sellars began his career with the National Park Service in 1966 as a seasonal ranger-naturalist at Grand Teton National Park. He then pursued a PhD in American history at the University of Missouri–Columbia, which he completed in 1972. He returned to the NPS in 1973 in Denver, often teaching staff how to manage historic sites. From 1979 to 1988 he served as the Southwest Regional chief of historic preservation, architecture, and archaeology and also oversaw a Service-wide program in underwater archeology.

In 1989 he began an eight-year period devoted to researching the history of NPS natural resource management, which led to publication of his 1997 landmark book, *Preserving Nature in the National Parks: A History*. According to a 2012 High Country News article profiling Sellars, the work "charted the influence of agency administrators and landscape architects, whose tourism-driven agenda often eclipsed biologists' efforts to preserve ecological health." Reaction to the book ranged from widespread praise for focusing attention on the erratic development of natural resource management policy in the context of overall NPS policy to criticism as revisionist history that demonized past policies for making parks accessible.

The effect of the book was tremendous and immediate, elevating the need for science-based natural resource management to a high priority alongside NPS staples of serving and protecting visitors. By 1999, the National Park Service had announced its Natural Resource Challenge initiative, and over the next several years greatly increased the number of new scientific staff working for the bureau in parks, at 32 park networks, and at regional and national offices, all in support of meeting park science needs.

Sellars is the recipient of several top honors for his long-term contributions to the National Park Service and resource conservation: the Department of the Interior's Meritorious Service Award, the Coalition of National Park Service Retirees' George B. Hartzog Award, and the George Wright Society's George Melendez Wright Award for Excellence.

He retired from the National Park Service in 2008. Over his 35-year NPS career he influenced and educated many people through his historical research, writing, lecturing, and teaching, and occasionally challenged NPS traditions. PS

Research Reports

Mine tailings reclamation project improves water quality in Yellowstone's Soda Butte Creek

By Tom Henderson, Andrew Ray, Pete Penoyer, Ann Rodman, Mary Levandowski, Alysa Yoder, Shane Matolyak, Mary Beth Marks, and Autumn Coleman

MINING-RELATED DISTURBANCES ARE THE PRIMAry source of increased metals loading above natural background conditions in the Soda Butte Creek drainage straddling the northeastern boundary of Yellowstone National Park (Boughton 2001). Tailings on the McLaren Mill and Tailings site (hereafter McLaren site), bordering Soda Butte Creek near the town of Cooke City, Montana, were the most significant of these anthropogenic sources (Boughton 2001; MTDEQ 2002b). The segment of Soda Butte Creek downstream to the Montana-Wyoming border is an impaired water body identified under Section 303(d) of the Clean Water Act and is the only Clean Water Act–impaired water body entering Yellowstone National Park (O'Ney et al. 2011). In 2014, the Montana Department of Environmental Quality (DEQ) completed the McLaren Tailings Reclamation Project, culminating five years of environmental construction work. (See "Reclamation work at McLaren Mill and Tailings" on page 13 for more of the reclamation story.) In collaboration with the National Park Service's (NPS) Natural Resource Stewardship and Science Directorate Water Resources Division, this work was performed to remove the potentially unstable tailings impoundment, mitigate the metal loading to improve water quality, and enhance the ecological health of Soda Butte Creek. The reclamation project was preceded by 80 years of environmental impacts from the milling operation and discharges from the tailings impoundment (fig. 1). In 2015, NPS and Montana DEQ scientists initiated longitudinal studies of water quality in Soda Butte Creek to document water quality downstream of the reclaimed tailings site and during the initial phase of recovery.

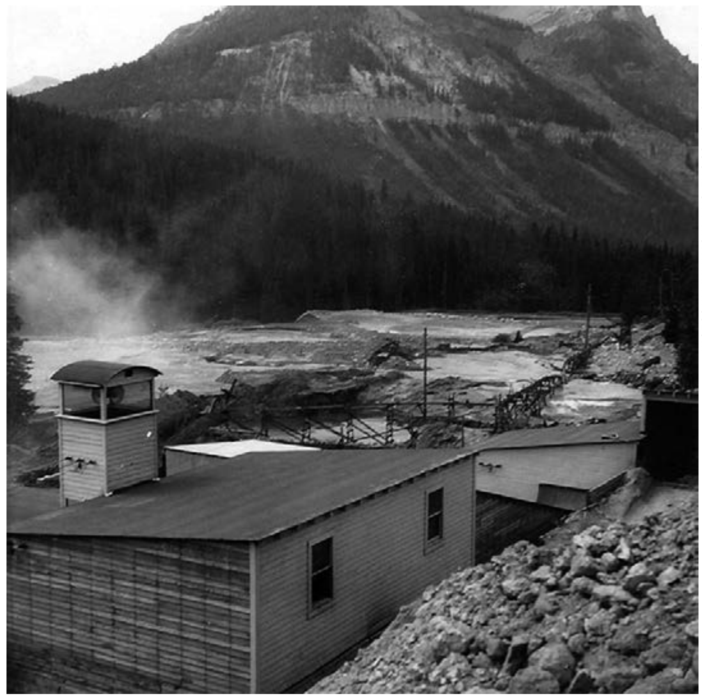

PHOTO COURTESY OF COOKE CITY MONTANA MUSEUM

Figure 1. McLaren Gold Mine Mill near Cooke City, Montana, in 1946. The tailings impoundment extends outward from the mill and is likely encroaching on Soda Butte Creek.

Abstract

In 2015, National Park Service scientists teamed with the Montana Department of Environmental Quality to conduct a comprehensive characterization of water quality in Soda Butte Creek. Soda Butte Creek is a tributary of the Lamar River whose water quality was impaired by historical mining activity near Cooke City, Montana. This investigation followed the reclamation of the McLaren Mill and Tailings site, a long-sought-after objective by Yellowstone National Park, the State of Montana, and local environmental groups. The tailings at the McLaren site had leached metals into Soda Butte Creek for more than 80 years and posed an ongoing threat to Yellowstone National Park. This investigation summarizes metal concentrations from a monitoring location downstream of the former McLaren site before and after the completion of reclamation work. It also provides a summary of a basin-wide water quality inventory completed in 2015 and 2016 and documents benthic sediment chemistry post-reclamation. Results from this investigation indicate significant improvements in water quality in the vicinity of the reclaimed McLaren site and a reduction in the number of water quality exceedances documented at the Yellowstone National Park boundary. Importantly, recent documented water quality exceedances are readily traced to two tributaries located outside the park boundary and not the former mill and tailings site.

Key words

303(d) list, abandoned mine lands, metals, mining, Soda Butte Creek, water quality, Yellowstone National Park

Setting and hydrology

Soda Butte Creek is an active, unregulated cobble- and gravel-dominated stream located in the Absaroka and Beartooth Mountains of Montana and Wyoming. It flows from the high mountains situated east of Yellowstone National Park west to meet the Lamar River; the creek enters the park at its northeast entrance (fig. 2, facing page). Within the watershed of Soda Butte Creek exist the small gateway communities of Cooke City and Silver Gate, Montana. Today, this region offers seasonal lodging and services to visitors of Yellowstone National Park. Outdoor enthusiasts and residents enjoy the mountainous setting year-round.

More than 150 years ago (and before the establishment of Yellowstone National Park in 1872) trappers and prospectors discovered gold, copper, and silver deposits in this region. At the time, the area was part of the Crow Reservation but reservation boundaries were redrawn in 1882 to the east, in part to support access to the region that later became part of the New World Mining District (Glidden 1982). Some of the place-names surrounding Cooke City and within the Soda Butte Creek watershed still bear the names given by early prospectors (e.g., Mineral Mountain and Silver Creek; fig. 2) and draw attention to the deposits that attracted miners to the region. (See "Mining history of the region" on page 13 for more information.)

Although mining in this metal-rich region has largely been abandoned, the legacy of mining contributed to the inclusion of a 5-mile (8 km) segment of Soda Butte Creek on Montana's list of impaired waters (i.e., 303(d) list). (See "Environmental legacy" on page 15 for further information.) On this list, Soda Butte Creek from Cooke City to the Montana-Wyoming border near the Yellowstone National Park boundary (see fig. 2) was determined to be impaired because of elevated levels of copper, iron, lead, and manganese (MTDEQ 1996). Elevated concentrations of these metals were attributed to Soda Butte Creek's contact with mine tailings from a gold processing facility, the McLaren site, located just east of Cooke City (Hill 1970; Duff 1972; Meyer 1993; Boughton 2001; fig. 1). Elevated metals also contributed to the stream's red appearance near Cooke City (fig. 3) where oxidized iron deposits blanketed the stream bottom (MTDEQ 2002b). This once-prized fishery was reported as having "fast-fishing and large trout" in the 1800s, but by 1931 the fishery was categorized as "fair to poor" (cited in USFWS 1979). Surveys of the reach in the early 1970s indicated that no trout were detected in surveys below the influent of tailings waters (Duff 1972; Chadwick 1974). In addition, an instream bioassay documented 80% mortality of fingerling trout following 48-hour exposure to Soda Butte Creek water collected downstream of McLaren site (Chadwick 1974). Based on this and other important work (see Nimmo et al. 1998), evidence overwhelmingly showed that reclamation activities were necessary to remove contributing sources of pollution. Following these recommendations, the US Forest Service (USFS) completed extensive mine reclamation work in the New World Mining District between 2000 and 2008 (USFS 1999b; USFS 2012). USFS-led work in the Soda Butte Creek drainage included waste removal and reclamation of the Great Republic Smelter site near Cooke City and reclamation of a portion of the McLaren Mill site. Both projects were completed in 2005 (USFS 2006). Reclamation of the McLaren site began in June 2010 and was completed in October 2014. The project included pumping and treating contaminated groundwater, removal of the tailings impoundment, and reconstruction of segments of Soda Butte Creek and Miller Creek, which had been impacted by the impoundment (MTDEQ 2009; MTDEQ 2015).


MONTANA DEPARTMENT OF ENVIRONMENTAL QUALITY

Figure 3. Oxidized iron sediments were the norm in Soda Butte Creek downstream of the McLaren Mill and Tailings site in 2009, prior to reclamation.

Investigation objectives

In spring 2015, the NPS Water Resources Division, Greater Yellowstone Inventory and Monitoring Network, and Yellowstone National Park teamed up with the Montana DEQ to conduct a longitudinal characterization of water quality in upper Soda Butte Creek including the characterization of conditions in tributaries from the McLaren site to the Yellowstone National Park boundary (fig. 2). Our overarching goal of this work was to assess the water quality during the initial phase of recovery and post-reclamation. To that end, we had the following specific objectives: (1) compare metal concentrations from a location downstream of the McLaren site before and after the completion of reclamation work, (2) inventory metals throughout the upper Soda Butte Creek drainage and assess basin-wide water quality, and

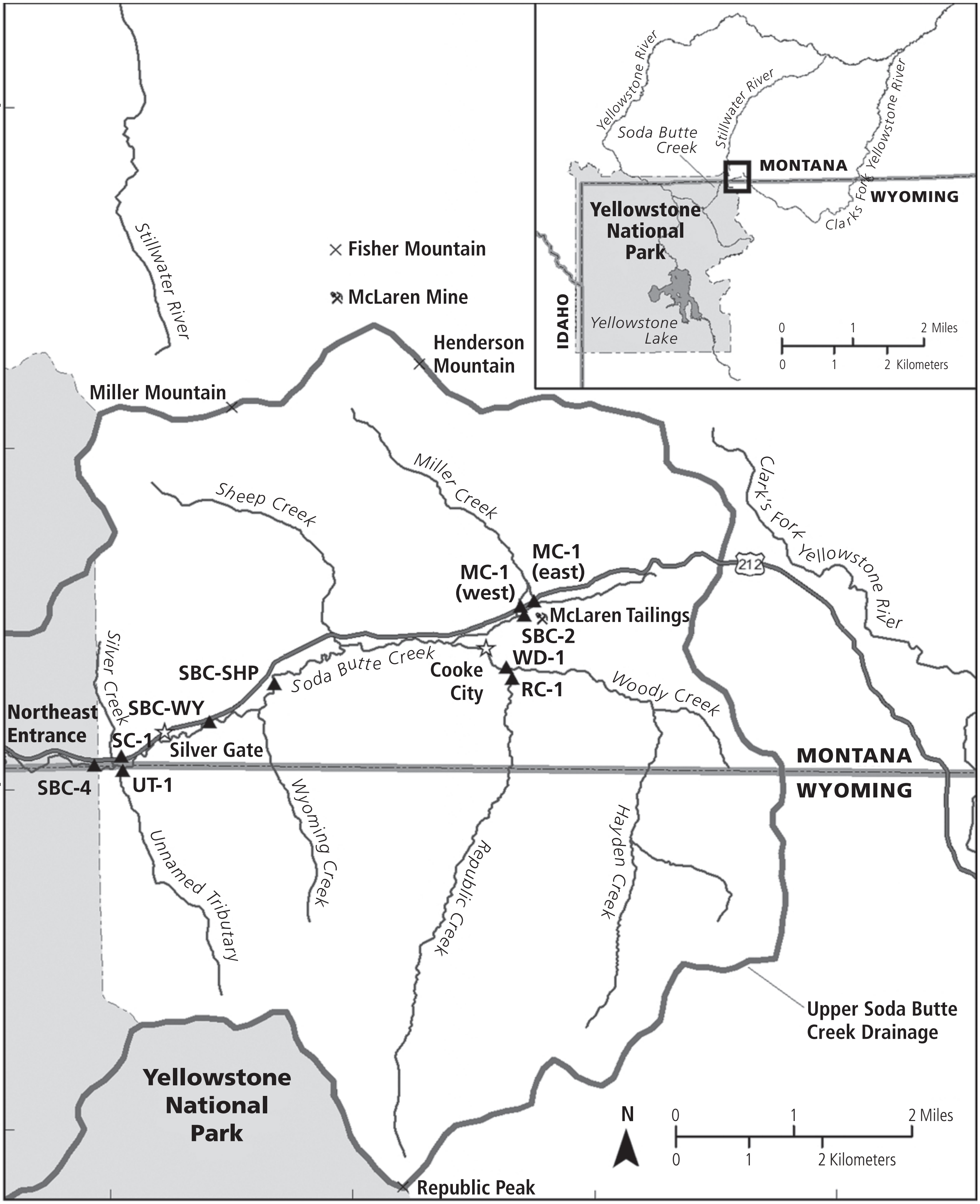

Figure 2. The map depicts the upper Soda Butte Creek watershed including tributary streams. Cooke City and Silver Gate are indicated by open stars, water quality sampling locations by black triangles. Sampling locations include MC-1 east and MC-1 west (the two forks of Miller Creek above the Soda Butte Creek confluence), SBC-2 (Soda Butte Creek below McLaren site), WD-1 (Woody Creek above Republic Creek confluence), RC-1 (Republic Creek above Woody Creek confluence), SBC-SHP (Soda Butte Creek below Sheep Creek), SBC-WY (Soda Butte Creek below Wyoming Creek), UT-1 (an unnamed tributary near the Yellowstone park boundary), SC-1 (Silver Creek), and SBC-4 (Soda Butte Creek at the Yellowstone National Park boundary).

This investigation summarizes metal concentrations from a monitoring location downstream of the former McLaren site before and after the completion of reclamation work.

(3) document benthic sediment chemistry post-reclamation to consider how it aligns with current water quality data from Soda Butte Creek's main stem and tributaries.

Methods

Basin-wide water quality and sediment chemistry characterization was completed using samples collected from the following locations: Miller Creek above the Soda Butte Creek confluence (MC-1 east and MC-1 west are the two forks of Miller Creek), Soda Butte Creek below McLaren site (SBC-2), Woody Creek above the Republic Creek confluence (WD-1), Republic Creek above the Woody Creek confluence (RC-1), Soda Butte Creek below the confluence of Sheep Creek (SBC-SHP), Soda Butte Creek below the confluence of Wyoming Creek (SBC-WY), an unnamed tributary near the Yellowstone National Park boundary (UT-1), Silver Creek (SC-1), and Soda Butte Creek at the Yellowstone National Park Boundary (SBC-4). For this summary, results from MC-1 east and MC-1 west were averaged for each sampling date and reported as MC-1 in the results. Yellowstone National Park, US Forest Service (USFS), and US Geological Survey (USGS) scientists have completed sampling at these and additional main stem Soda Butte Creek sites over the last two decades (see USFS 1999a; Boughton 2001).

Discharge patterns in Soda Butte Creek are dynamic in time and space. To reconstruct flows for the Soda Butte Creek below the McLaren site (SBC-2) sampling location, we first developed an empirical log-log relationship between discrete discharge measurements (n = 12) collected at SBC-2 and the USGS Soda Butte Creek gage (USGS 06187915) located at the Yellowstone National Park Boundary (SBC-4) between June 2015 and June 2016. We calculated discharge estimates at the SBC-2 sampling location since 2000 using the following statistically significant linear relationship:

$$\log \text{SBC-2 discharge (cfs)} = -0.526 + (0.864 \times \log \text{SBC-4 discharge [cfs]};\ R^2 = 0.932,\ P < 0.001)$$

Water collection (2000–2010)

The US Forest Service contracted with Tetra Tech (formerly Maxim Technologies) to monitor surface water quality during implementation of the New World Response and Restoration Project. Water quality samples were collected using grab techniques from the thalweg (interval exhibiting the largest flow or highest velocity) in accordance with the project water monitoring plan (USFS 1999a). Sample bottles provided by the analytical laboratory were triple rinsed with native water prior to sample collection, preserved as necessary, and placed into coolers with ice for shipment to the laboratory (Pace Analytical, Billings, Montana).

Water collection (2015–2016)

We used depth- and width-integrated sample collection techniques to gather representative water samples from each location. Samples were collected using a DH-81 sampler (Federal Interagency Sedimentation Project, Vicksburg, Mississippi; fig. 4)

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Figure 4. Water sampling in Soda Butte Creek downstream of the McLaren Mill and Tailings site in November 2015 following reclamation.

Reclamation work at McLaren Mill and Tailings

Given the ongoing contamination of Soda Butte Creek and the risk of a catastrophic tailings release, Montana DEQ's preferred alternative was the complete removal of the tailings impoundment from the Soda Butte Creek floodplain (MTDEQ 2002a). The tailings impoundment covered an area of approximately 10 acres (4 ha) and included approximately one-half million tons of mine tailings and approximately one million gallons of contaminated groundwater. Groundwater discharging from the impoundment contaminated the underlying aquifer, which contained groundwater under confined pressures (MTDEQ 2009).

In order to meet the objective of complete removal of the impoundment, project design and construction work included a significant groundwater pumping and treatment effort. Dewatering the tailings was achieved by capturing uncontaminated groundwater around the perimeter of the tailings impoundment and from the aquifer below the impoundment. The pumped water was sent to a water treatment plant to treat the water to achieve Montana water quality standards. More than 110 million gallons (0.4 million m^3) of contaminated water were pumped and treated during active reclamation. The contaminated water was treated using calcium hydroxide to increase the pH and precipitate dissolved metals. Treated water was discharged to Soda Butte Creek with daily field monitoring and weekly laboratory analysis to document water quality (MTDEQ 2015). Calcium oxide was mixed with tailings to neutralize acidity in the tailings and dry the tailings for compaction in the constructed repository. Approximately 1,800 lineal feet (550 m) of Soda Butte Creek and Miller Creek channels were reconstructed in their approximate pre-mining locations following the removal of the tailings impoundment in 2013. The project was covered with compost-amended soil and seeded in 2014. Construction costs, including water treatment and site reclamation work, totaled $21,897,249 (MTDEQ 2015). The work was funded by annual grants from the Department of the Interior Office of Surface Mining Reclamation and Enforcement and a grant from the Montana Department of Natural Resources and Conservation Reclamation and Development Grants Program. The project earned a National Recognition Award from the American Council of Engineering Companies in 2015.

Mining history of the region

Following gold discoveries in the early and mid-1860s, prospectors traveled throughout the Montana Territory in search of another bonanza. A small party of prospectors found gold in stream deposits in the area of Fisher Creek and Upper Soda Butte Creek in 1869. Mining started in the 1870s on Republic Mountain and Miller Mountain, which border Soda Butte Creek (GCM Services, Inc. 1998). A new mining camp developed, named Cooke City, after Philadelphia financier Jay Cooke visited the camp in 1879 and promised to build a railroad to the area. Over the subsequent decades, Cooke City fluctuated from a few dozen residents in lean times to hundreds when the mines were active (GCM Services, Inc. 1985). By 1920 the town had two ore smelters, two steam sawmills, three general stores, and two hotels (Lovering 1929; Reed 1950). The deposits included lead-silver ore from Miller Mountain, gold-copper ore from Henderson and Fisher Mountains, and copper ore mined near the headwaters of the Stillwater River (fig. 2).

Operating from 1934 to 1953, the McLaren Gold Mines Company (fig. 1) was one of the longest-running, last active mining operations in the area. Ore containing gold, silver, and copper was extracted from an open cut mine on Fisher Mountain 3 miles (5 km) north of Cooke City and trucked to the McLaren Mill built on the north bank of Soda Butte Creek near Cooke City (fig. 1). In the 1930s, the mine was a small-scale operation and was suspended when the mill burned down. In 1940 the McLaren Mill was rebuilt, and the mine operated steadily until 1953, processing approximately 185 tons of ore daily. The resulting concentrates were trucked to Gardiner, Montana, and then shipped by railroad to the Anaconda smelter west of Butte. The total production of the operation amounted to approximately 60,000 ounces of gold, 170,000 ounces of silver, and 4 million pounds of copper (Krohn and Weist 1977; GCM Services, Inc. 1985).

and composited and homogenized in a 2 gal (8 l) churn sample splitter. All sample collection and splitting equipment was triple rinsed with native water prior to sample collection. Sample bottles provided by the laboratory were triple rinsed from the churn prior to filling. Once rinsed, water was dispensed from the churn into bottles. Metal samples were preserved in the field using concentrated nitric acid (HNO_3). Sample containers were shipped to one of two analytical laboratories (ChemTech Ford, Sandy, Utah, or Energy Laboratories, Billings, Montana) over the course of the study; submitted water was analyzed for total metals. Split samples offered opportunities to look at congruence among laboratory results.

We also characterized field water quality physiochemical parameters (e.g., NPS core parameters; Rosenlieb et al. 2002) including temperature, specific conductance, dissolved oxygen concentration, and pH in situ using multiparameter water quality meters at a minimum of three locations on the cross section during all sampling events. This data set is not shown here but is available upon request.

Sediment collection and analysis

We collected benthic sediment samples in the stream cross section at seven sites throughout the upper Soda Butte Creek watershed on 4 and 5 August 2015. Approximately 5 ounces (150 ml) of material was collected at the water-sediment interface from three locations (0.25, 0.50, and 0.75 times the total cross-sectional length). All benthic samples were transported to the Mineralogy Lab at Montana State University in Bozeman, Montana, for processing. To remove moisture and organic materials, samples were first baked at 160–180°F (70–80°C) for three hours. Dried samples were then crushed to a fine powder (grain was ≤10 μm in diameter). Once powdered, each sample was placed into an X-ray fluorescence pellet and sealed with an X-ray penetrable plastic film. Individual samples were placed in the powder X-ray fluorescence analyzer for 122 seconds and the elemental composition of sediments was estimated.

Results

Water quality pre- and post-reclamation below McLaren site

Monitoring location SBC-2 is located in the main stem of Soda Butte Creek immediately downstream of the location of the McLaren site. A branch of Miller Creek discharges to Soda Butte Creek upstream of this monitoring location (fig. 2). Pre-reclamation water quality was characterized using the USFS water quality data set compiled from April 2000 through April 2010 and using the same sampling reaches.

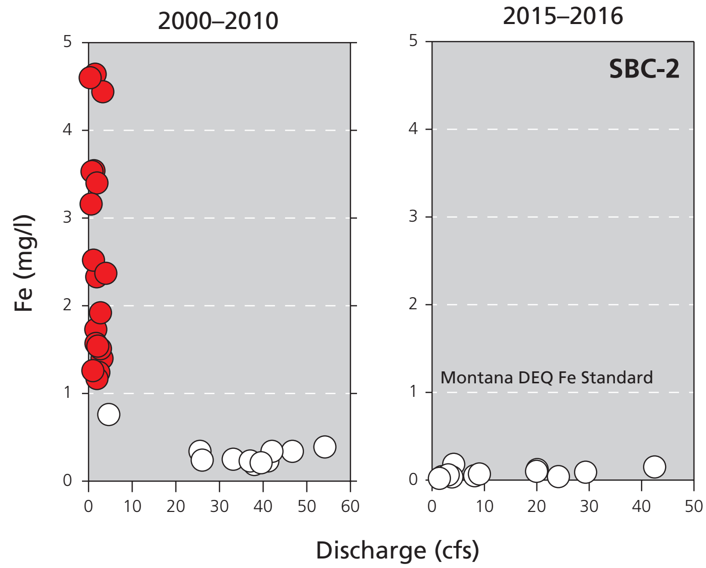

Figure 5. Historical and current iron concentrations from quarterly (2000–2010; pre-reclamation) and monthly (2015 and 2016; post-reclamation) water samples collected from Soda Butte Creek below McLaren site (SBC-2). Water samples meeting the Montana iron standard are shown in white and those exceeding the standard are shown in red. Excluded from this figure (for presentation reasons) was a low flow water sample collected pre-reclamation on 9 April 2009 that had an iron concentration of 27.4 mg/l (result that was 5 times higher than the next highest pre-reclamation sample). Discharge at SBC-2 was estimated using an empirical relationship (see methods) between discharge measured at SBC-2 and discharge measured at the USGS Soda Butte Creek gage (USGS 06187915) located at the Yellowstone National Park boundary (SBC-4). Water samples collected pre-reclamation regularly exceeded the Montana iron standard during low flows. Samples collected post-reclamation met the standard across all discharge levels.

Water quality results from monitoring location SBC-2 (fig. 2) reveal that exceedances of iron (fig. 5) and copper occurred annually from 2000 to 2010. During this period, iron exceeded the Montana water quality standard (1.0 mg/l) in 20 of the 31 samples collected (65%). These iron exceedances generally occurred during low flow conditions. From the 11 samples collected between June 2015 and June 2016 and following the completion of reclamation activities, no exceedances of iron were documented immediately downstream from McLaren site (fig. 5).

Copper and lead water quality standards are a function of measured water hardness. Copper exceedances of the Montana hardness-based water quality standard were less common than iron exceedances prior to reclamation activities, but occurred in 8 of the 31 samples (26%) and typically during high flows. In contrast, only a single copper exceedance was documented in 2015 and 2016 following reclamation. Prior to reclamation, one lead exceedance was documented in 2003. There were no documented lead exceedances below McLaren site after reclamation activities.

Environmental legacy

During operation of the McLaren Mill, tailings disposal was problematic as overflow from the tailings impoundment flowed downstream into Yellowstone National Park. Inspections by park rangers documented a regular pattern of leaks and breaks in the earthen dike surrounding the tailings impoundment (Glidden 2001). As the daily operation of the mill tended to give a milky appearance to Soda Butte Creek, the frequent breaks and washouts of the impoundment had more serious consequences (Johnson 1949). A dam break occurred during summer 1950 that was caused by a series of heavy rainstorms and flash floods in the upper Soda Butte Creek basin. A ranger inspecting the area on 28 June of that year documented repairs made to the impoundment but noted that similar breaks in the dam occurred each spring and more breaks could be expected with continued operation of the mill (Johnson 1950). Years later, Meyer (1993) mapped bright orange-red sediments containing elevated levels of iron, copper, and lead from Cooke City more than 15 miles (24 km) downstream and concluded that the likely source was the 1950 release.

The Yellowstone fires of 1988 and concerns with failure of the tailings dam resulted in a heightened awareness of the potential threat of McLaren site to the park (Kauf and Williams 2004). Given the history of dam failure and added threats associated with altered runoff patterns following the 1988 fires, McLaren site was designated an Emergency Response Action Site by the US Environmental Protection Agency. Response measures included work to armor the margins of the impoundment, improve the stability of the dam, and reduce the amount of water flowing onto the impoundment (MTDEQ 2002a). At that same time, the Montana DEQ was completing the Water Quality Restoration Plan for the Cooke City TMDL Planning Area to improve water quality to a level that would restore beneficial uses (MTDEQ 2002b).

During this period, the US Forest Service established 13 long-term surface water monitoring stations as a component of the New World Response and Restoration Project (USFS 1999a; USFS 1999b). Monitoring generally occurred at or near winter base flow conditions (April), during high flow conditions (June), and during fall low flow conditions (September and October). The monitoring network included multiple sites on Soda Butte Creek and sites in a major tributary (Miller Creek). Importantly, these monitoring data can now be used to characterize variations in water quality over the decade preceding the reclamation of McLaren site (see fig. 2).

Current Montana water quality standards do not include a numeric standard for manganese (MTDEQ 2012). However, the US Environmental Protection Agency (EPA) has established a National Secondary Maximum Contaminant Level (SMCL) for manganese at 0.05 mg/l (USEPA 2017). Prior to reclamation, manganese concentrations exceeded the EPA SMCL in 14 of the 31 samples (45%) collected from 2000 through 2010. None of the 11 post-reclamation samples contained manganese above the SMCL.

Water quality pre- and post-reclamation at the Yellowstone National Park boundary

At the park boundary (SBC-4), exceedances of iron and copper were not as common as they were below McLaren site (SBC-2). From 2000 to 2010 a total of 6 iron, 3 copper, and 4 lead exceedances were documented at SBC-4 from the 31 sampling events conducted during the decade before reclamation. In addition, one sampling event indicated manganese exceeded the EPA SMCL. Post-reclamation, we documented only 2 iron exceedances during 11 scheduled sampling events. There were no documented exceedances of copper, lead, or manganese. Median iron concentration at the park boundary prior to reclamation was 0.62 mg Fe/l; post-reclamation we documented a median concentration of 0.53 mg Fe/l.

Current assessment of water quality in the Soda Butte Creek drainage

Between June 2015 and June 2016, we completed 11 water quality sampling visits to main stem and tributary locations in the Soda Butte Creek watershed (see fig. 2 for sampling locations). An additional tributary location (Miller Creek, MC-1) was added in 2016 and five samples were collected from that site from April to June 2016. Over the 13-month period, we collected samples during multiple high, intermediate, and low flow events.

Iron concentrations were low (median = 0.13 mg/l; range 0.02 to 0.42 mg/l) directly below McLaren site (SBC-2) compared to

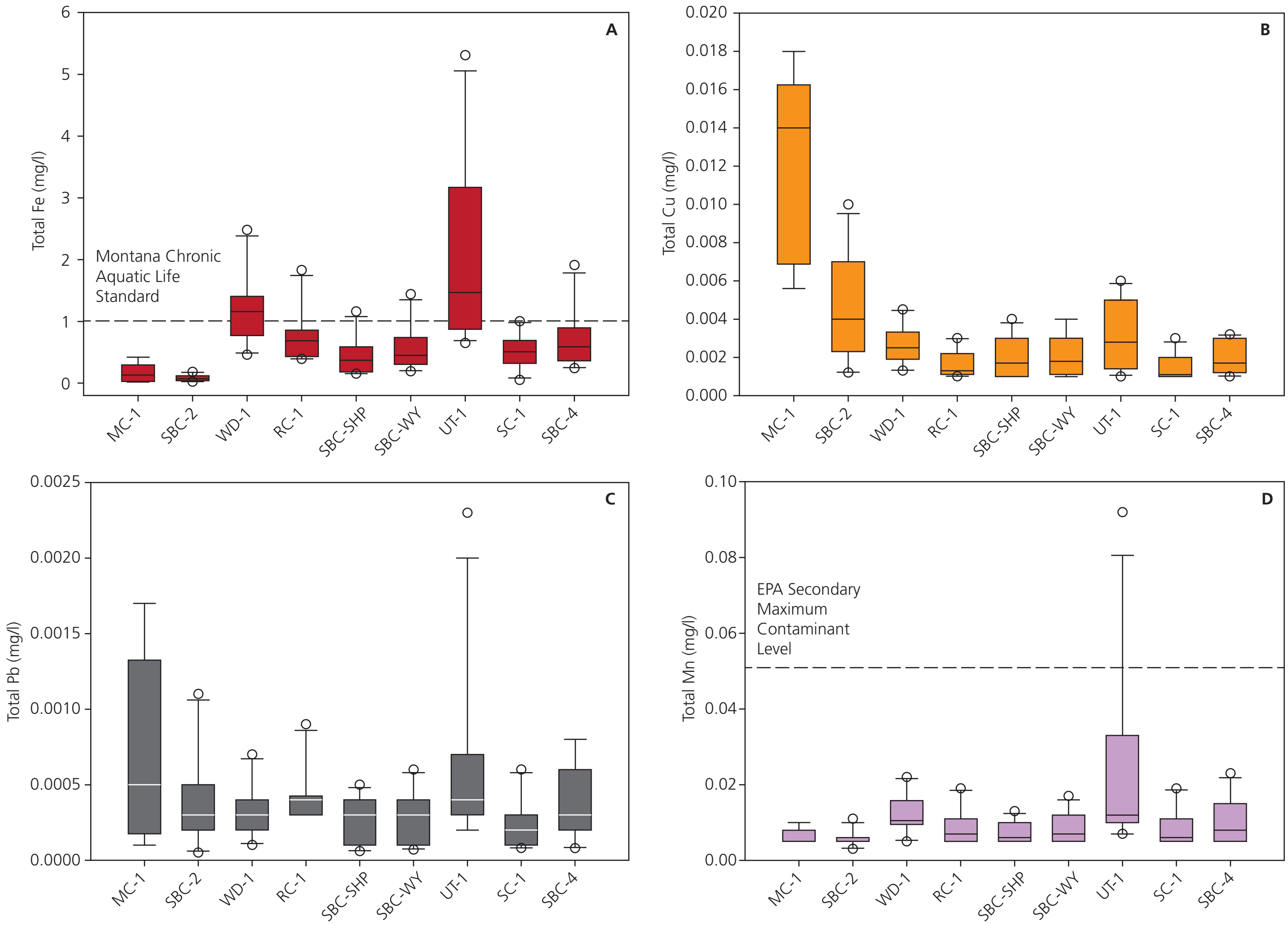

Figure 6. Box whisker plots show total iron (A), copper (B), lead (C), and manganese (D) concentrations from water samples collected from nine sampling locations in the upper Soda Butte Creek watershed (see fig. 2 for sampling location descriptions) from June 2015 through June 2016. Median iron and manganese concentrations were highest in Woody Creek (WD-1) and the unnamed tributary (UT-1); the Montana Chronic Aquatic Life Standard of 1 mg/l and the EPA's National Secondary Maximum Contaminant Level for manganese of 0.05 mg/l are shown. Copper and lead water quality standards are a function of measured water hardness. Median copper concentrations were highest in Miller Creek (MC-1). Lead concentrations were variable across sites but lead concentrations in Woody Creek and the unnamed tributary exceeded the Montana standard during runoff in 2016.

all other monitoring locations (fig. 6A). From June 2015 to June 2016 median iron concentrations were highest in two tributaries: Woody Creek (WD-1, median = 1.16 mg/l; range 0.46 to 2.48 mg/l) and an unnamed (and undeveloped) Soda Butte Creek tributary (UT-1, median = 1.47 mg/l; range 0.65 to 4.04 mg/l) just east of the Yellowstone National Park boundary (fig. 2). Iron concentrations in Woody Creek and the unnamed tributary exceeded water quality standards on 70% and 64% of sampling visits, respectively (fig. 7). Concentrations of iron at the park boundary were strongly positively correlated (Spearman Rank R = 0.773, P = 0.004) with concentrations in the unnamed tributary just outside the park boundary.

Copper levels were highest in Miller Creek (MC-1), a tributary that drains from the mineral-rich region (New World Mining District) north of the project site, directly into the reclamation site. Median copper levels in Miller Creek were 3.5 to >10 times higher than median levels of copper for all other sites including the main stem Soda Butte Creek (fig. 6B). Copper concentrations in the unnamed tributary also exceeded Montana's hardness-based standard for copper on five sampling occasions.

Lead concentrations for all main stem Soda Butte Creek sites were below Montana's hardness-based water quality standards. Lead concentrations in Woody Creek and the unnamed tribu-

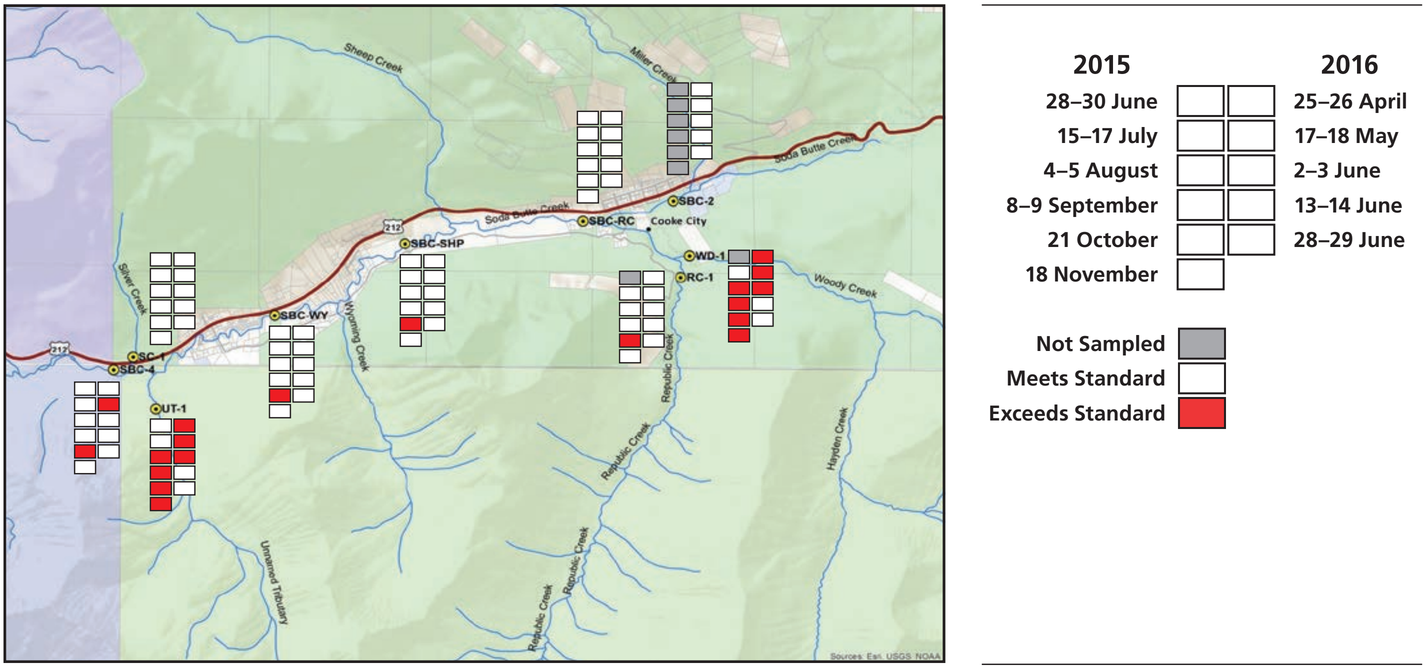

Figure 7. Map of the upper Soda Butte Creek watershed showing total iron exceedances from 11 sampling occasions and nine locations (see fig. 2 for sampling location descriptions) between June 2015 and June 2016. Red boxes indicate an exceedance of the Montana Chronic Aquatic Life Standard of 1 mg/l. White boxes indicate iron concentrations were below the Montana standard. Iron concentrations exceeded the standard on most occasions in two tributaries: Woody Creek (WD-1) and an unnamed tributary (UT-1). Elsewhere, iron exceedances were uncommon (RC-1, SBC-SHP, SBC-WY, and SBC-4) or not detected (MC-1, SBC-2, and SC-1). Gray boxes indicate a site was not sampled on a given date.

tary exceeded the water quality standard during runoff in 2016; the unnamed tributary also exceeded the lead standard during a rain-generated runoff event in August 2015 (fig. 6C). Manganese was detected above the EPA SMCL only in the unnamed tributary during a single sampling event (2 June 2016; fig. 6D).

Benthic sediment chemistry

Sediment iron levels were significantly lower in Soda Butte Creek below the former McLaren site (SBC-2; 2.64% or 26,384 ppm iron), but similar (averaging 4.5% or 45,046 ppm iron across sites) in main stem and tributary reaches downstream of that location (fig. 9A, page 18). In general, there was a positive relationship between iron in benthic sediments and median concentrations of iron documented in water samples collected from June 2015 to June 2016 (fig. 8, right).

In contrast to patterns for iron, copper and lead concentrations associated with benthic sediments were highest in the main stem of Soda Butte Creek immediately below McLaren site at SBC-2. While benthic sediments were not collected from Miller Creek (MC-1), this tributary contributes significantly to the total copper and lead loads documented in waters at SBC-2 (fig. 9B and 9C, page 18) and in downstream reaches of Soda Butte Creek that were sampled below McLaren site.

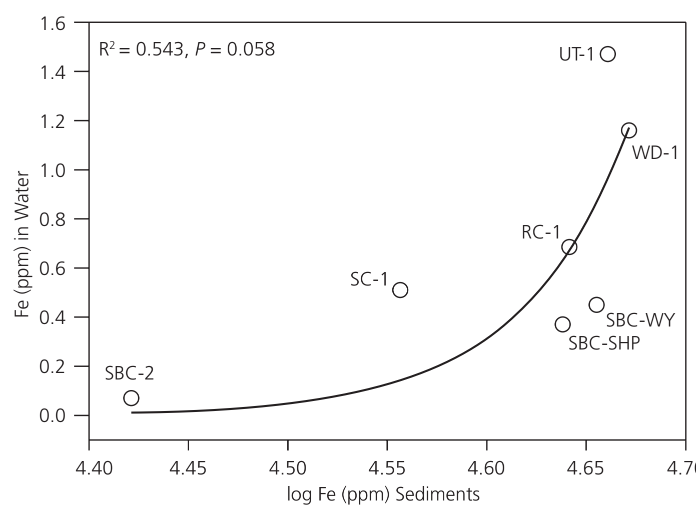

Figure 8. In the upper Soda Butte Creek watershed, benthic sediment iron and water iron concentrations are positively related. Sampling sites with higher average sediment iron concentration (e.g., Woody Creek [WD-1]) tended to have higher concentrations of iron in surface water. See fig. 2 for sampling location descriptions.

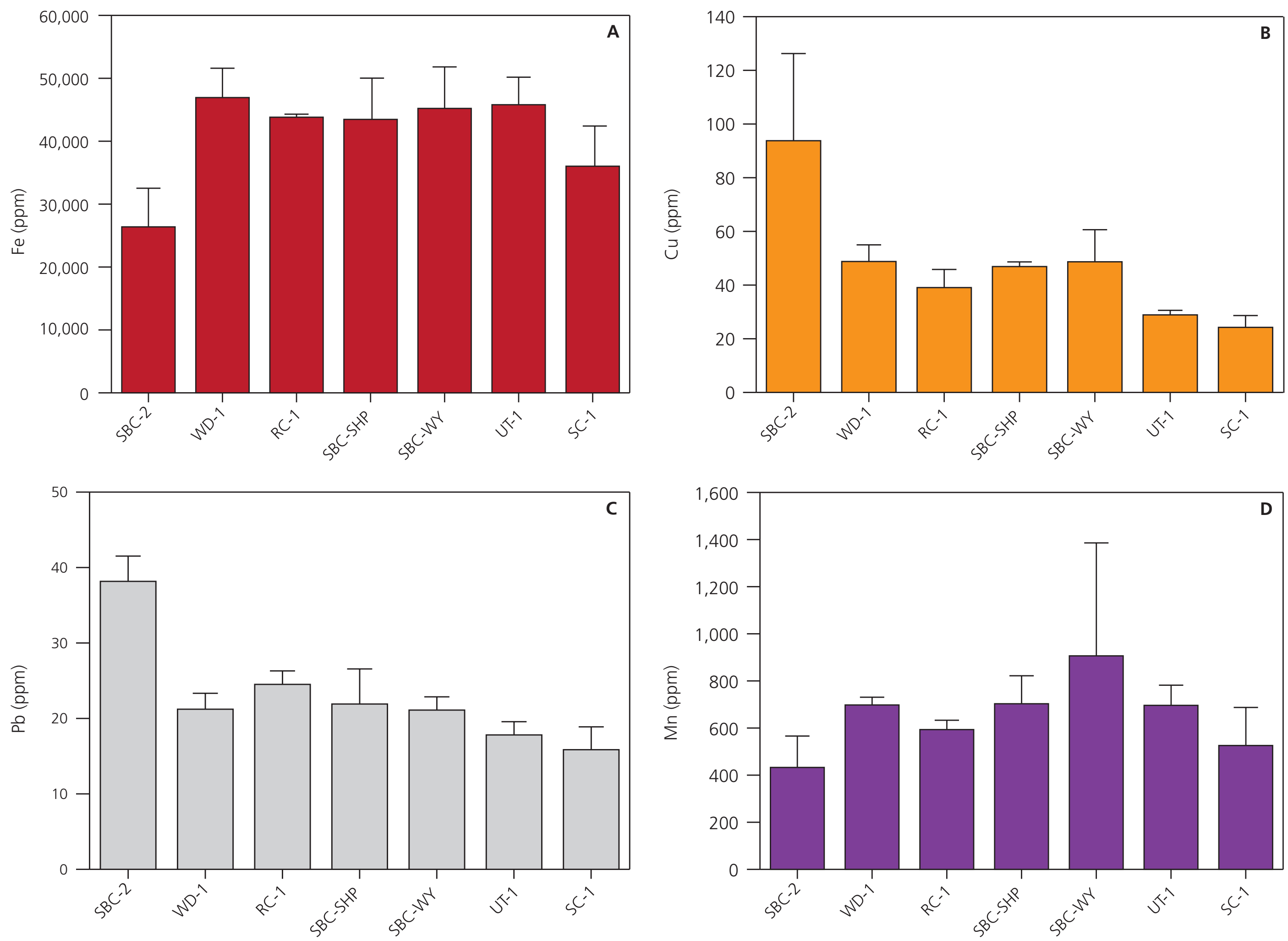

Figure 9. The bar graphs show concentrations of benthic sediment iron (A), copper (B), lead (C), and manganese (D) (in ppm [mg/kg equivalent]) for seven sampling locations (see fig. 2 for sampling location descriptions). Sediment iron was lowest in Soda Butte Creek below the McLaren site (SBC-2). Sediment copper and lead were highest at SBC-2.

Discussion

Previous studies identified both natural and anthropogenic sources contributing to metal loads measured in Soda Butte Creek upstream of Yellowstone National Park. These studies identified the highest concentrations of metals in the watershed below the tailings of the former McLaren Mill and Tailings site. For example, Boughton (2001) documented concentrations of iron, copper, and lead (418 mg/l Fe, 6.08 mg/l Cu, and 0.603 mg/l Pb, respectively) in a seep below the tailings dam that exceeded Montana water quality standards by two to three orders of magnitude. USFS data from 2000 to 2010 confirm that exceedances of iron and copper were common in Soda Butte Creek below McLaren site prior to reclamation. Using this and other historical water quality data (Hill 1970; Chadwick 1974; Nimmo et al. 1998), the Montana DEQ estimated that a 99% reduction in total metal loads from the McLaren site was needed to restore beneficial uses (i.e., designated goals, societal values, or fish and wildlife benefits associated with a water body) in Soda Butte Creek (MTDEQ 2002b).

The current investigation shows that reclamation of McLaren site effectively eliminated this known anthropogenic source of iron, copper, lead, and manganese in the drainage. Water quality test results indicate that tributaries, rather than the main stem of Soda Butte Creek below McLaren site, now introduce waters with the highest concentrations of metals. Woody Creek and the unnamed tributary both regularly exceeded Montana's water quality standards for metals. Importantly, exceedances of metal standards were rare at main stem sites and occurred only at sampling locations downstream of these tributary inputs.

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Figure 10. Soda Butte Creek downstream of the McLaren Mill and Tailings site in 2008 shows contamination by orange-colored iron (left) that is not evident in 2013 (right) following cleanup.

Benthic iron levels below McLaren site measured in 2015 (2% to 3% iron) are near background levels for floodplain and benthic sediments of this region (Meyer 1993; Hren 2001; fig. 5). More importantly, current levels of iron are significantly lower than those in the former McLaren tailings impoundment (21% iron) and pre-reclamation sediments downstream of the former mill site (8% to 16% iron; Meyer 1993). However, copper and lead levels in sediments below McLaren site were generally higher than at other monitoring locations. While sediments were not measured from Miller Creek, that tributary discharges to Soda Butte Creek from the north and above our SBC-2 sampling location (fig. 2). Natural erosion of the ore-bearing region to the north of the project site produces metal-rich waters that have contributed to regional water chemistry since the Pleistocene (Furniss et al. 1999; Hren et al. 2001). Sediments transported in these flashy, high-gradient streams may have deposited in the main stem of Soda Butte Creek and contributed to the elevated copper and lead levels documented. It is also possible the elevated copper and lead concentrations in sediments documented at SBC-2 are attributable to pre-reclamation discharges from McLaren site. The latter interpretation, however, is inconsistent with the low concentration of iron detected in sediments at this location (fig. 9).

Taken as a whole, the investigation reveals significant improvements in the Soda Butte Creek water below the McLaren site (see fig. 10). Current water quality exceedances at the Yellowstone National Park boundary appear to be limited to iron. Iron in Soda Butte Creek is readily traced to two tributaries neither of which has any identified mine-land disturbances. At least one of these tributaries (the unnamed tributary) has no evidence of significant anthropogenic activity such as from roads or trails. As a result, water quality conditions in Soda Butte Creek now appear to be dominated by non-anthropogenic sources of metals.

The reclamation of the McLaren site represents a milestone in the … restoration of Soda Butte Creek from mining-related impacts and culminates 15 years of coordinated work between the National Park Service and the Montana DEQ.

Concluding remarks

The reclamation of the McLaren site represents a milestone in the assessment and restoration of Soda Butte Creek from mining-related impacts and culminates 15 years of coordinated work between the National Park Service and the Montana DEQ. The improvement in water quality has facilitated the return of beneficial uses to the Greater Yellowstone Ecosystem. For example, the multiagency Soda Butte Creek Yellowstone Cutthroat Trout Conservation Project was initiated in 2015 to protect and secure habitat for Yellowstone cutthroat trout (*Oncorhynchus clarkii bouvieri*) in the Soda Butte Creek drainage and the greater Lamar River watershed (MTFWP 2015). The return of salmonids and inclusion of Soda Butte Creek in this conservation plan offer testament to the fact that the ecological recovery of Soda Butte Creek is advancing.

The collaboration between the Montana DEQ and the National Park Service was critical to the planning and execution of the McLaren Tailings Reclamation Project. This group venture also made possible the current inventory of water quality in the upper Soda Butte Creek drainage and those data led to a determination in November 2017 by the Montana DEQ Water Quality Bureau that metals conditions in Soda Butte Creek support all designated beneficial uses. At the time of this writing, the EPA has concurred with this recommendation. As a result, the Montana DEQ has recommended removing Soda Butte Creek from the 303(d) Impaired Waters List. For the Montana DEQ and its project partners, this marks the first time in Montana that a water body has been proposed for delisting from the 303(d) Impaired Waters List for metals following the successful implementation of abandoned mine cleanup.

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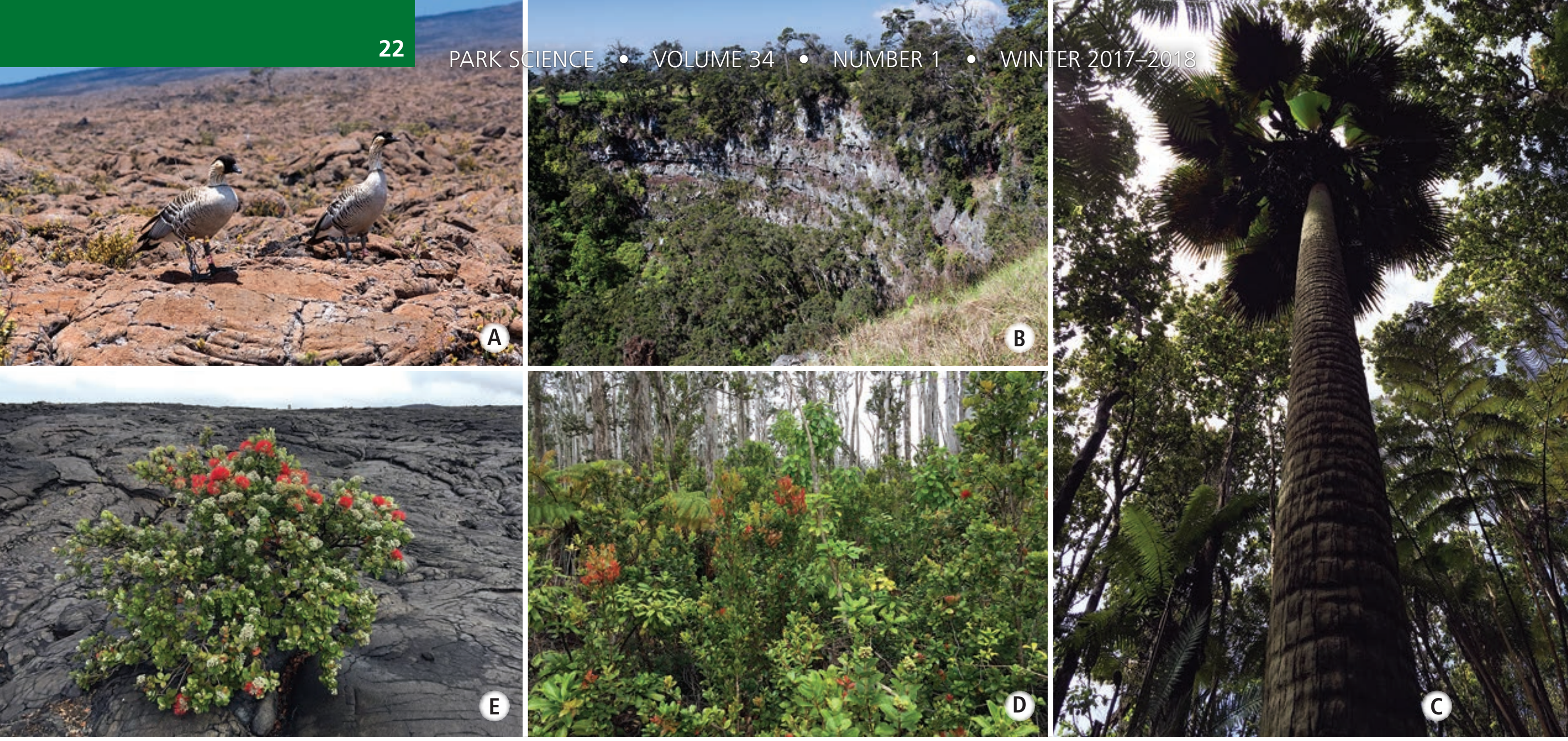


(ALL) HAWAI`I VOLCANOES NATIONAL PARK/MARK WASSER

Potential impacts of projected climate change on vegetation management in Hawai`i Volcanoes National Park

By Richard J. Camp, Rhonda Loh, S. Paul Berkowitz, Kevin W. Brinck, James D. Jacobi, Jonathan Price, Sierra McDaniel, and Lucas B. Fortini

MORE THAN 1,000 NATIVE PLANT SPECIES EXIST IN the state of Hawai`i, most of which are found nowhere else on Earth. Nearly one-third of these are listed as endangered or threatened by the US Fish and Wildlife Service. Hawai`i is also host to numerous invasive plant species that have spread across the landscape, often excluding natives that evolved in their absence. Because patterns of rainfall and temperature in the Hawaiian Islands are shifting and expected to continue to change into the future, managers at Hawai`i Volcanoes National Park want to know how climate change may shift plant distributions, especially in the park's highly managed Special Ecological Areas (SEAs), focal sites managed for perpetuating native plant communities and endangered species (Loh et al. 2014) (fig. 1). Under future climate conditions, these protected areas may no longer be suitable for the native species that currently inhabit them. In addition, park managers want to know if expanding invasive species may pose a threat to areas where native plants predominate, thus requiring additional management and resources. To address these concerns, we used bioclimatic envelope models to determine future habitat suitability. Bioclimatic envelope models are based on associations between climate conditions and species' occurrences to estimate the habitats suitable to maintain viable populations (Araújo and Peterson 2012).

Global climate conditions, including but not limited to increased global temperatures, changing circulation and precipitation patterns, increased ocean acidification, and sea-level rise, are changing (IPCC 2014). These changing conditions result in changes to physical, biological, and human-managed systems. Future climate conditions are projected with global climate models (GCMs) using atmospheric and oceanographic factors. GCMs have a coarse horizontal resolution of 100 km (62 mi) or more. Thus the typical horizontal resolution of GCMs does not adequately represent the small-scale topographic features and climate variation of the Hawaiian Islands (Giambelluca et al. 1986). Accurately characterizing diverse and complex island microclimates requires downscaling of the GCM grid to regional and local scales. Dynamic downscaling is a technique that uses the large-scale conditions provided by the GCMs to drive a local-scale meteorological model with a much higher resolution (Gutmann et al. 2012). The International Pacific Research Center (School of Ocean and Earth Science and-

Figure 1 (above). Each of the habitat types pictured here was part of the modeling: (A) Lowland dry habitat where native vegetation is projected to contract. (B) Mesic habitat where species richness may decrease by half. (C) Wet habitat with plants that may contract to outside the park. (D) Wet habitat expected to transition to mesic habitat. (E) Dry habitat expected to become mesic and more favorable.

Abstract

Climate change will likely alter the seasonal and annual patterns of rainfall and temperature in Hawai`i. This is a major concern for resource managers at Hawai`i Volcanoes National Park where intensely managed Special Ecological Areas (SEAs), focal sites for managing rare and endangered plants, may no longer provide suitable habitat under future climate. Expanding invasive species' distributions also may pose a threat to areas where native plants currently predominate. We combine recent climate modeling efforts for the state of Hawai`i with plant species distribution models to forecast changes in biodiversity in SEAs under future climate conditions. Based on this bioclimatic envelope model, we generated projected species range maps for four snapshots in time (2000, 2040, 2070, and 2090) to assess whether the range of 39 native and invasive species of management interest are expected to contract, expand, or remain the same under a moderately warmer and more variable precipitation scenario. Approximately two-thirds of the modeled native species were projected to contract in range, while one-third were shown to increase. Most of the park's SEAs were projected to lose a majority of the native species modeled. Nine of the 10 modeled invasive species were projected to contract within the park; this trend occurred in most SEAs, including those at low, middle, and high elevations. There was good congruence in the current (2000) distribution of species richness and SEA configuration; however, the congruence between species richness hotspots and SEAs diminished by the end of this century. Over time the projected species-rich hotspots increasingly occurred outside of current SEA boundaries. Our research brought together managers and scientists to increase understanding of potential climate change impacts, and provide needed information to address how plants may respond under future conditions relative to current managed areas.

Key words

bioclimatic envelope modeling, climate change, Hawai`i Volcanoes National Park, management strategies, plant distributions, precipitation, protected area prioritization, Special Ecological Areas (SEAs), species range, temperature

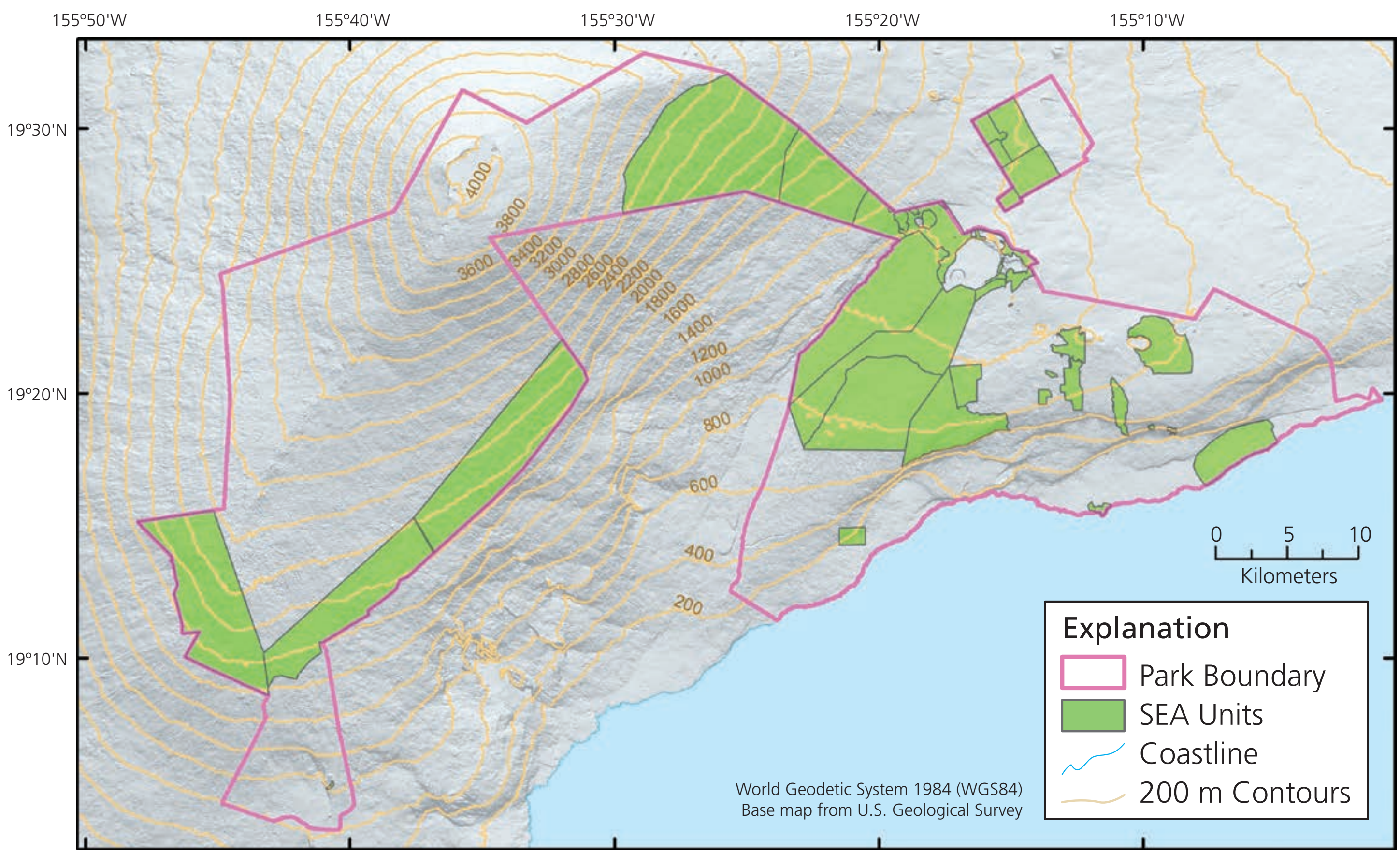


Figure 2. Location of Special Ecological Areas (SEAs) at Hawai`i Volcanoes National Park. SEAs are highlighted in green, while the park boundary is outlined in pink, coastline in blue, and 200 m (656 ft) contours in gold.

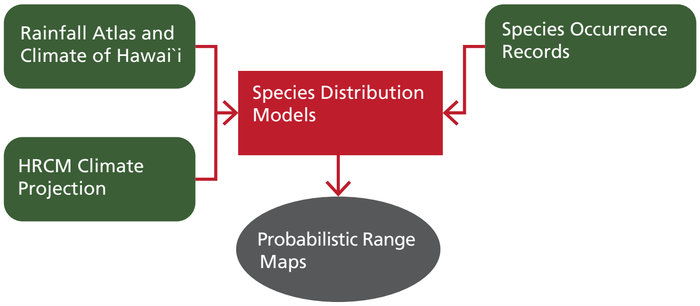


Figure 3. Flowchart depicting bioclimatic envelope model input data (present climate, future climate, and species occurrence records) and processing steps (species distribution models and scaling) used to produce probabilistic range maps. The Hawaii Regional Climate Model (HRCM) is a dynamically downscaled climate model exhibiting a moderately warmer and more variable precipitation future climate scenario. Probabilistic range maps were mapped at 80% threshold generated from 400 model iterations, based on different starting and ending climatic conditions. Round-edged boxes represent data, square-edged boxes represent processing steps or models, and the oval represents output.

Technology, University of Hawai`i at Mānoa) recently completed dynamic downscaling of GCMs for the present day and the end of the 21st century for the Hawaiian Islands (Zhang et al. 2012, 2016a, 2016b).

Changes in climate conditions will drive changes in species distribution, resulting in changes to the composition of plant communities (Price et al. 2012). A recent study by Fortini et al. (2013) examining climate-based species distribution shifts in the context of habitat area, quality, and distribution illustrated that many native Hawaiian plants may be particularly vulnerable to climate change, resulting in major range changes for much of the Hawaiian flora. Furthermore, Foden et al. (2013) and Fortini et al. (2013) have found the Hawaiian plant species most vulnerable to climate change also tend to be those that are most susceptible to existing nonclimatic threats (e.g., competition with or predation by invasive species, habitat loss due to changing land use), suggesting conservation challenges for these species will become increasingly difficult over time.

As a result of climate change and concomitant shifting habitat, resource managers at Hawai`i Volcanoes National Park have considered the need to adjust their current focal conservation areas to ensure that important species and plant communities continue to be protected over time. Intensive vegetation management at the park is focused on Special Ecological Areas (fig. 2, previous page), which are roughly configured to protect representative plant communities and important species by controlling the most invasive incipient and established invasive plant and animal species (Loh et al. 2014). Park managers therefore want to know if the current configuration of SEAs will continue to provide protection for focal plant communities and species of concern in the future. Likewise they want to know what new and possibly novel communities may occur in the future within, and adjacent to, the currently configured SEA boundaries. The answers to these questions are likely to suggest revisions to their strategies for future management and protection of the park's important plant resources.

Methods

Figure 3 illustrates the modeling process used to compute species range by combining current (Giambelluca et al. 2013, 2014) and future (Zhang et al. 2012, 2016a, 2016b) climate conditions with records of plant species occurrence from the Price et al. (2012) range models. We modeled the ranges of 29 native and 10 invasive focal plant species statewide, focusing on changes within the national park SEAs (Camp et al. in press). We incorporated bioclimatic factors (volcano boundaries, substrate age, and elevation) from the Price et al. models with current and future projected rainfall and temperature to model species ranges. We obtained rainfall and temperature data from the Rainfall Atlas and Climate of Hawai`i (Giambelluca et al. 2013, 2014) based on the climatological period 1978–2007. For future projections, we used the projected differences in rainfall and temperature between the end-of-century (2080–2099; hereafter 2090) and current (1990–2009) dynamically downscaled climate models from the Hawaii Regional Climate Model (HRCM; Zhang et al. 2012, 2016a, 2016b). Under the A1B emission scenario (balanced energy sources) from the "Special Report on Emissions and the Coupled Model Intercomparison Project Phase 3" (CMIP3) protocol, the HRCM projects moderate warming of 2.5°C (4.5°F) and an increase in precipitation variability across most of Hawai`i by 2090. These climate projections allowed us to model the geographic ranges of plant species in 2090. Following Morrison and Hall (2002) we defined species range as the spatial arrangement of suitable habitats, and species distribution as the subset of range where species actually occur. Our projections therefore represent species range.

We modeled the range of 39 species identified by park resource managers (Rhonda Loh) as influential to the management of ecologically sensitive areas such as Hawai`i Volcanoes National Park SEAs (table 1). Based on the HRCM, we interpolated projected temperature and rainfall for four points in time (beginning-of-century or current [2000], 2040, 2070, and end-of-century [2090]) following a linear trajectory between them.

Table 1. Plant species influential in the development of Hawai`i Volcanoes National Park management strategies for ecologically sensitive Special Ecological Areas

Scientific Name	Hawaiian/Common Name	% Suitable Park Area	Net % Change
Native species			
Acacia koa	Koa	13	−13
Alyxia stellata	Maile	27	21
Cheirodendron trigynum	ʻŌlapa	3	−87
Cibotium spp.	Hāpuʻu	4	−80
Coprosma ernodeoides	Kūkaenēnē	51	−27
Coprosma montana	Mountain pilo	49	16
Coprosma spp.	Pilo	13	−48
Dicranopteris linearis	Uluhe	6	−87
Diospyros sandwicensis	Lama	14	75
Dodonaea viscosa	ʻAʻaliʻi	100	22
Freycinetia arborea	ʻIeʻie	4	−77
Ilex anomala	Kāwaʻu	4	−82
Leptecophylla tameiameiae	Pukiawe	66	−27
Metrosideros polymorpha	ʻŌhiʻa lehua	81	13
Myoporum sandwicense	Naio	100	16
Myrsine lessertiana	Kōlea lau nui	6	−88
Nestegis sandwicensis	Olopua	15	38
Osteomeles anthyllidifolia	ʻUlei	75	26
Pandanus tectorius	Hala	17	16
Pipturus albidus	Māmaki	6	−86
Pisonia spp.	Pāpala kēpau	10	−43
Psychotria hawaiiensis	Kōpiko ʻula	4	−79
Psydrax odorata	Alaheʻe	11	28
Rubus hawaiensis	ʻĀkala	10	−59
Sadleria cyatheoides	ʻAmaʻu	47	−20
Santalum spp.	ʻIliahi	99	27
Sophora chrysophylla	Māmane	22	−4
Vaccinium calycinum	ʻŌhelo kau lāʻau	1	−97
Vaccinium reticulatum	ʻŌhelo	51	−36
Invasive species			
Clidemia hirta	Koster's curse	3	−55
Falcataria mollucana	Albizia	1	−78
Hedychium gardnerianum	Kahili ginger	1	−93
Lantana camara	Lantana	13	63
Miconia calvescens	Miconia	1	−86
Morella faya	Faya tree	5	−88
Passiflora tarminiana	Banana poka	0	−100
Psidium cattleianum	Strawberry guava	4	−72
Rubus ellipticus	Himalayan raspberry	0	−100
Schinus terebinthifolius	Christmas berry	5	−11

Notes: Average percentage suitable habitat in 2090 was calculated as the species-specific suitable habitat (area that remained suitable plus expansion) divided by the area of the park times 100%. Projected net percentage changes in range between 2000 and 2090 were computed as the difference between the 2090 and 2000 percentage of park suitable divided by the 2000 percentage of park suitable times 100% (note differences because of rounding of reported values).

We produced each range model using a series of grids (with a resolution of approximately 250 m [820 ft]), on which we performed logical and mathematical operations. Climate models exhibit a great deal of uncertainty (Lauer et al. 2013) in their predictions, which presents complications when applying them in ecological forecasts. To incorporate uncertainty, we modeled each possible change from 20 years of current climate (1990–2009) to 20 years of end-of-century climate (2080–2099), yielding a total of 400 possible change values over the century. We then used an 80% threshold to map species ranges at each time step (Epstein and Axtell 1996); we considered a pixel (location) to be within the species range if it had an 80% or higher probability of being suitable habitat—that is, if it was suitable in ≥320 of the 400 possible climate projections. Based on projected species ranges, we calculated the change in range between current and future projections.

For the purposes of this study, the 147 SEA management blocks represent too fine a unit for examining changes in species range. Based on discussions with Hawai`i Volcanoes National Park resource managers, we aggregated these management blocks into 37 SEAs representing appropriately sized units for analyzing shifts in species range.

We quantified the net percentage change in species range for the national park and each SEA, and classified the amounts of contraction and expansion as minimal (≤20% change), moderate (20–50% change), or substantial (>50% change). The most desirable levels of change for natives are minimal contraction and substantial expansion, whereas for invasives the reverse is preferred.

We further evaluated each SEA by assessing the change in species richness between the current and end-of-century projections for the 29 modeled native species. Although this group represents only a subset of native species found within Hawai`i Volcanoes National Park, our richness index may be indicative of wider community shifts. We considered SEAs that maintained or increased native richness as optimally situated for future conditions, whereas SEAs that lost more than half of their current native species richness may require further investigation.

Results

Under the moderately warmer and more variable precipitation climate scenario considered, the net percentage change in the 29 native species modeled range is expected to be negative across Hawai`i Volcanoes National Park (table 1) and within the 37 SEAs. In 15 of the SEAs, native species ranges may contract substantially, including the SEAs around the lower portion of Mauna Loa Strip and around Kīlauea Crater, areas that receive intense visitation

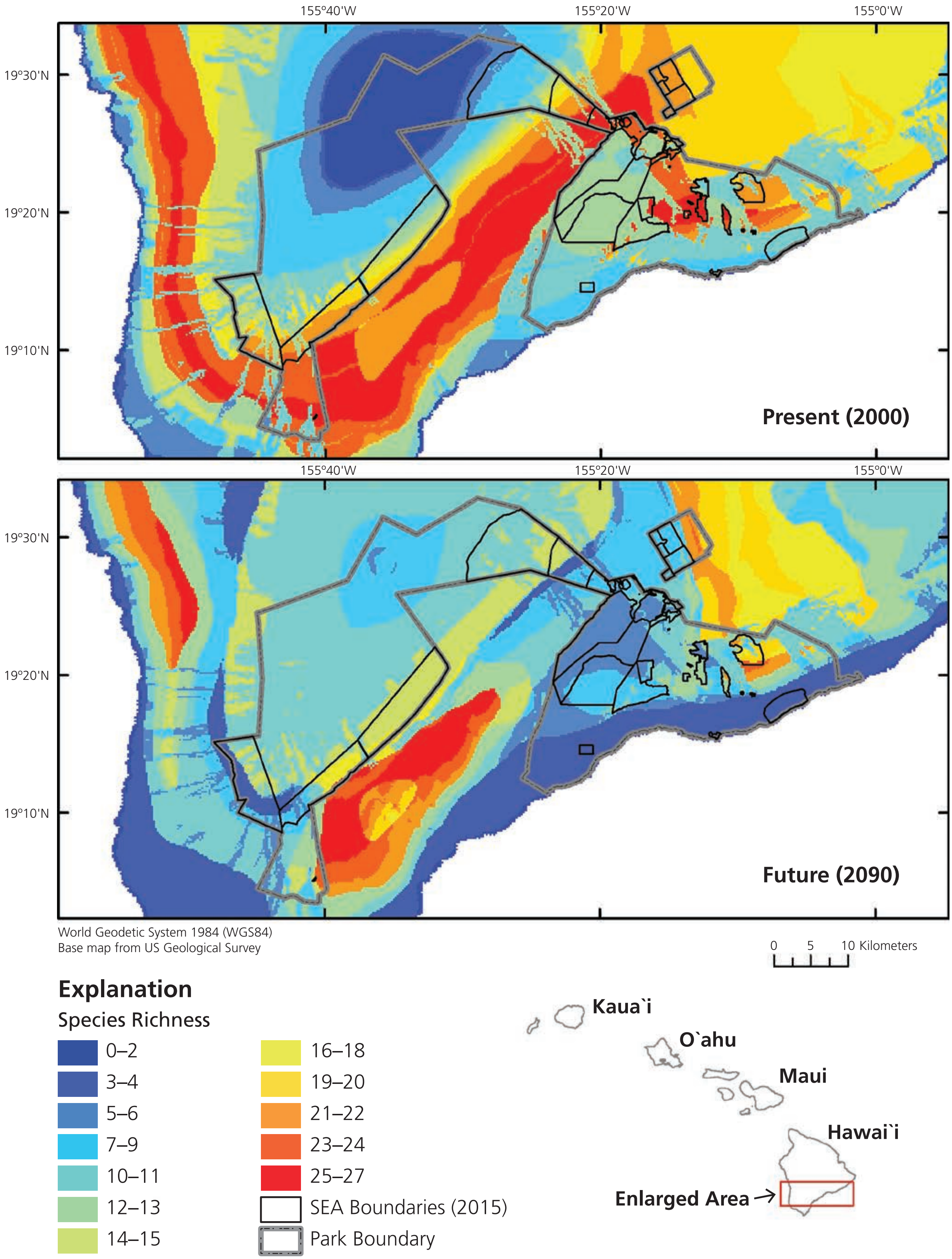
Changes in climate conditions will drive changes in species distribution, resulting in changes to the composition of plant communities.

and also are important for cultural practitioners. In six SEAs, native species contractions were spread among minimal, moderate, and substantial categories. In 14 SEAs (12 occurring below 1,200 m [3,937 ft] elevation), native species contractions were split about evenly between minimal and substantial contractions. Two SEAs showed predominantly minimal contractions.

We projected a negative percentage change for 9 of the 10 invasive species modeled across the national park (table 1) and in all 37 SEAs, except for *Lantana camara* and *Schinus terebinthifolius*, which showed mixed results ranging from substantial contractions to substantial expansions in several SEAs. Most invasive species showed minimal expansion under the future climate scenario considered. However, our projected models for the invasive plant species are likely conservative estimates of their potential range since many of these invasive species have yet to reach equilibrium in Hawai`i.

At present, good congruence exists between native species richness and SEA locations (top panel of fig. 4). The congruence, however, was projected to break down over time, and by the end of the century many of the existing SEAs occur in areas with limited habitat suitability for most native species of concern (bottom panel of fig. 4). Of particular interest were the forecasted remnant hotspots on the eastern edge of the Mauna Loa Southwest Rift tract, eastern portion of Olaa tract, and areas south and east of the East Rift tract, as we projected these areas to remain relatively rich (≥ 19 overlapping native species).

Figure 4 (opposite). Native species richness (29 modeled species) using cool to warm colors to represent overlapping distributions of few to many species, respectively. The top panel shows that the present (year 2000) distribution of hotspots in the national park aligns well with the distribution of SEAs. As shown in the lower panel, projected species richness at the end of the century (year 2090) predominately recedes from the national park, resulting in few species hotspots within SEA boundaries.


155°40'W
155°20'W
155°0'W
19°30'N
19°20'N
19°10'N
Present (2000)
Future (2090)
World Geodetic System 1984 (WGS84)
Base map from US Geological Survey
0 5 10 Kilometers
Explanation
Species Richness
0–2
3–4
5–6
7–9
10–11
12–13
14–15
16–18
19–20
21–22
23–24
25–27
SEA Boundaries (2015)
Park Boundary
Kaua`i
O`ahu
Maui
Hawai`i
Enlarged Area

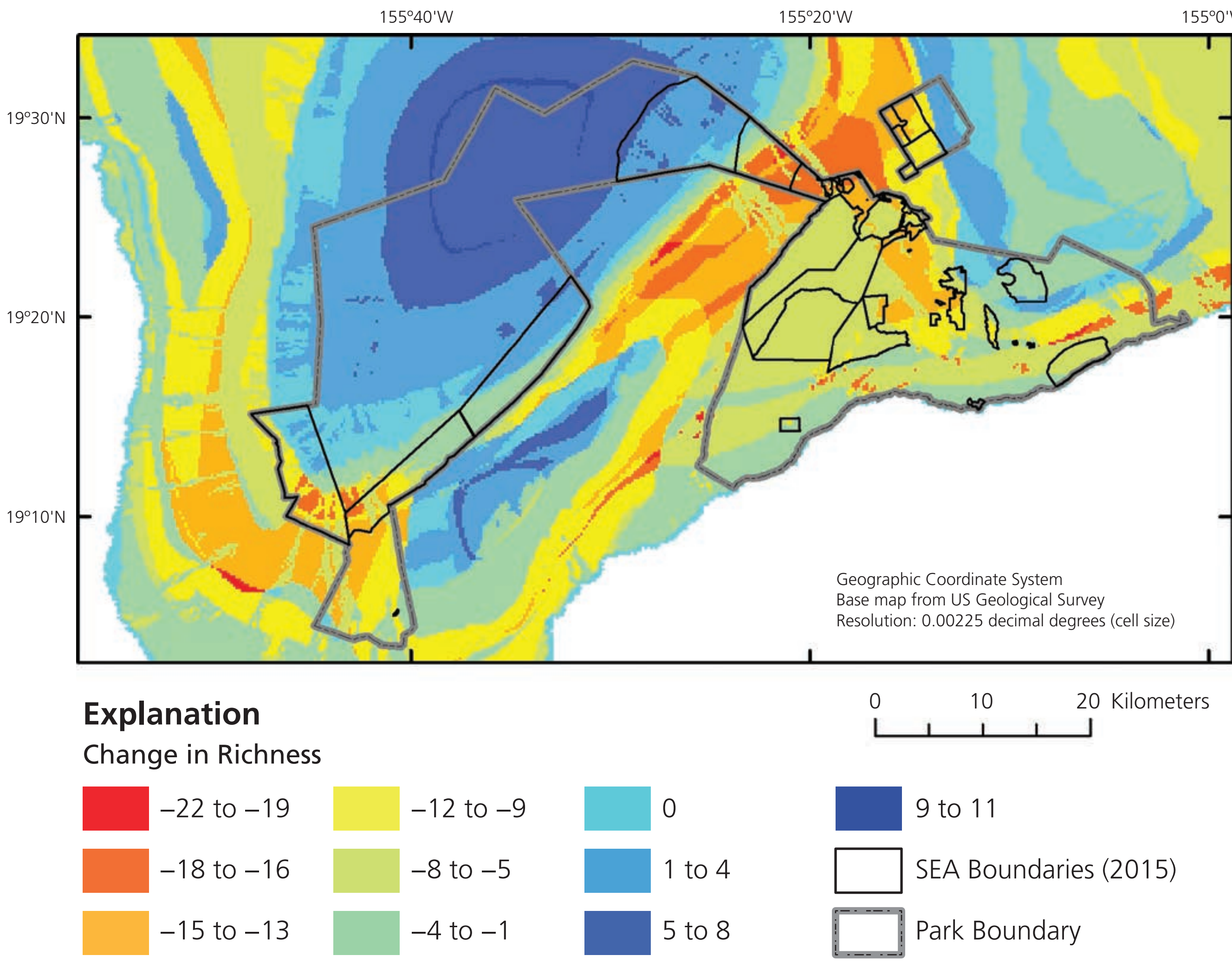


Figure 5. Change in native species richness from present (year 2000) to future (year 2090) for the 29 modeled native species. Note that negative values represent a decrease in suitable habitat by the year 2090, while positive values indicate an increase over the same time period.

A direct application of our projections is that they can be used to identify locations where major changes in habitat conditions are predicted (e.g., stable wet habitats transitioning to mesic habitats and even to dry habitats) and where plants are projected to respond under future conditions similar to the modeled climate scenario. We addressed this by computing the difference in species richness between the current and end-of-century projections (fig. 4) to generate a map of predicted species turnover (fig. 5). Areas with high species turnover occur where projected climate change effects are strongest.

Discussion and management

Climate is a key determinant of species distribution. Geophysically explicit species range modeling offers a powerful option for evaluating plant species response to future climate conditions. Based on relationships of current climate conditions in which a species has been observed, models can be used to predict species responses to forecasted climates (Chen et al. 2011). Forecasted species ranges may be used to focus management on maintaining species where the climate is projected to threaten their existence, as well as to facilitate establishment of SEAs at Hawai`i Volcanoes National Park in areas where species may be expected to shift.

Our end-of-century forecasted species ranges were consistent with other species range modeling for Hawai`i (Price et al. 2012, 2015; Fortini et al. 2013) where species range depends largely on climate (i.e., precipitation and temperature), substrate age, and historical distribution. Assuming an A1B scenario, the HRCM dynamically downscaled end-of-century climate conditions are forecast to have generally warmer temperatures and more variable

Increasing the size of SEAs, and improving habitat connectivity among them, would better accommodate range shifts of individual species and facilitate their dispersal into more hospitable environments.

precipitation. Under this scenario, species range contractions generally are expected to occur in coastal areas and lower elevations, while expansion of suitable conditions is expected to occur primarily in upper-elevation montane and subalpine habitats.

At Hawai`i Volcanoes National Park approximately two-thirds of the modeled native species (18 of 29) were projected to exhibit net range contraction, while about one-third (11 of 29) showed expansion. The species that showed the largest contractions typically have restricted bioclimatic requirements under current conditions. Because of the predominance of range contractions and limited range expansions, we projected a majority of the current SEAs will lose most of the native species we modeled, especially those SEAs occurring below 1,200 m (3,397 ft) elevation. Net range expansion typically occurred for the limited number of species that colonize pioneer, young lava flows where subalpine and alpine environments were projected to become suitable habitat under future precipitation and temperature regimes, i.e., when bioclimatic requirements of the plants and climate change metrics matched (Garcia et al. 2016).

Within the national park, the forecasted amount of range contraction exceeded expansion for all but one modeled invasive species (*Lantana camara*). These contractions are expected to occur in most SEAs, including SEAs at low, middle, and high elevations. Suitable habitat for only 4 of the 10 invasive species (*Clidemia hirta*, *Lantana camara*, *Morella faya*, and *Schinus terebinthifolius*) will likely persist throughout most of the park's SEAs. These results for invasive species may help managers by reducing the need for control measures for this set of invasive species and benefiting some native species by reducing competition. However, any interpretation of range changes for invasive plant species should be made cautiously. The modeled ranges are limited to reported distributions in Hawai`i, and might not reflect the full physiological limits of these species. Additionally, other invasive species besides those modeled in this study are expected to continue to occupy these habitats, and their range may expand or contract in response to climate change (Vorsino et al. 2014).

Forecasted shifts in suitable habitat for native plant species will assist park managers in assessing configuration of and prioritizing future work in SEAs (Watson et al. 2013). Under forecasted end-of-century climate projections where drier areas become drier, wetter areas become wetter, and temperatures increase everywhere, but more so at high elevations (Elison Timm et al. 2011; Zhang et al. 2012, 2016a, 2016b), our results suggest that the congruence between species richness hotspots and SEAs will diminish over time. As such, by the end of the century many projected species hotspots occurred outside of current SEA boundaries.

While the trajectory and extent to which climate change and plant response remain to be validated, managers can reasonably consider expanding existing SEAs or establishing new SEAs in areas where future diversity hotspots are likely to occur. Increasing the size of SEAs, and improving habitat connectivity among them, would better accommodate range shifts of individual species and facilitate their dispersal into more hospitable environments.

Similarly, the results from this modeling can assist national park managers working with adjoining landowners and partner agencies to prioritize conservation work island-wide. Hawai`i Volcanoes National Park collaborates with several state, federal, and private landowners to protect more than a million acres (400,000 ha) of watershed on the island of Hawai`i as a member of the Three Mountain Alliance (TMA). Protection of native species diversity and invasive species management are among the TMA activities that would benefit directly from this modeling and its forecasted shifts in species ranges.

Obtaining additional habitat data in areas projected to experience the greatest climate change, for example deploying weather stations, will help managers understand the trajectory and extent of climate change. In addition, vegetation monitoring will provide information on how plants are responding to these measured changes in conditions.

While current resource management actions (e.g., fencing and control of ungulates, invasive species control, outplanting native plants) will continue to be critical for conservation of plant species and communities, the rate of climate change is an additional factor that will affect habitat suitability. If, for example, climate change is very rapid, the predicted changes in suitable habitat for some native species might grossly underestimate the realized changes in future distribution if these natives cannot adapt rapidly to changing conditions or compete effectively with invasives in order to realize their potential. Assisted colonization, the translocation of organisms outside their historically documented ranges in anticipation of more suitable future conditions, may be a conservation option for consideration. Candidate species, such as *Diospyros sandwicensis*, *Nestegis sandwicensis*, and *Psydrax odorata*, for assisted colonization include those that possess long generation times, have low reproductive rates, lack the dispersal capability needed to track rapidly changing climate conditions, or occur close to their physiological limits (Chauvenet et al. 2013; Rout et al. 2013; Gallagher et al. 2015). Once established, additional management actions such as supplementing introduced populations may be necessary to maintain viable populations and communities (Moir et al. 2012).

The tropics have a relatively small range of natural climate variability (Mora et al. 2013; Power 2014). However, in our models most species' suitable habitat ranges changed substantially by century's end. Based on which rate of climate change is being followed as the century unfolds, our projections allow managers to update their decisions at intermediate management cycles (Stephenson 2014).

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1 Output data from the models used to assess potential impacts of projected climate change on vegetation management strategies are published at https://www.sciencebase.gov/catalog/item/5362af3ee4b0c409c6289bc7.

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Changes over 30 years in populations of the leafcutter ant *Atta mexicana* at Organ Pipe Cactus National Monument

An analysis of long-term environmental impacts on population size and survival

Figure 1. Center of growing colony (2–3 years old) along transect 9, showing excavated soil in form of craters. A small, orange-brown fungus waste dump surrounds the small crater at the top left.

By Alex C. Mintzer

***ATTA MEXICANA* (F. SMITH) AT ORGAN PIPE CACTUS** National Monument, Arizona, provides an amazing example of survival and success at the northern limit of its range in the Sonoran Desert. Known as leafcutter ants, *Atta* spp. are ubiquitous objects of fascination in the dense forests of tropical America from Mexico to Argentina (Hölldobler and Wilson 1990), but their existence in the much drier environment of the Sonoran Desert of Arizona is a surprise to most observers. The main range of this ant species is in Mexico, with a southern limit in Guatemala and El Salvador (Smith 1963). These ants have been noted in an impressive diversity of habitats in Mexico, including oak and pine woodlands, mesquite grasslands, deserts, arid thorn scrublands, tropical short-tree deciduous forests, and tropical tall-tree deciduous and semideciduous forests (Smith 1963; Mintzer, personal observation based on extensive travel).

At Organ Pipe, this ant offers a unique interpretive opportunity, a natural history that has been related to thousands of visitors since 1987. Like other *Atta* species associated with tropical ecosystems, *A. mexicana* produces large central nests in this park, occupied by colonies that probably number in the millions of individual ants (fig. 1). These nests and colonies dwarf those produced by all other resident ant species (Mintzer 1987). The individual ants are large, and leaf-cutting and item-carrying behaviors of foraging ants draw attention from park visitors in the cooler months, when they are active during the daytime. At Organ Pipe, the colonies are dependable targets for interpretive walks led by ranger-naturalists (fig. 2).

The first record of *A. mexicana* at Organ Pipe was provided by Byars (1949), who collected them near a gravel pit 1 km (0.6 mi) north of the current park headquarters. Another collection was made by entomologist R. E. Gregg and his party in 1948. W. S. Creighton visited Organ Pipe in 1952, but did not encounter them in the park; this species is not listed in his comprehensive monograph of North American ants (Creighton 1950). George and Jeanette Wheeler (1983) published a photograph of the superstructure of a nest along the Puerto Blanco Drive. National Park Service staff has been aware of these ants in the national monu-

Abstract
The leafcutter ant *Atta mexicana* lives at the extreme northern margin of its range in the Sonoran Desert of Organ Pipe Cactus National Monument. This ant has a fascinating natural history that has been described to thousands of park visitors over the last 30 years. Because the National Park Service had had no knowledge of ant colony distribution or population size in the backcountry of Organ Pipe, in 1985 resource managers solicited and supported the first systematic survey. I used high-resolution aerial photographs to identify 11 arroyo channel transects with suitable habitat in the southern third of the park along the international boundary. We walked these transects in December 1985 and again in 1995, 2005, and 2015, to determine the local colony abundance and distribution of this rare ant and study long-term changes in this park population. These decadal surveys revealed that the population size undergoes major fluctuations, and also showed that typical field colony lifespans are 10–20 years. Population decreases by late 2005 raised concerns for long-term population viability, in light of potential challenges presented by increased borderland agricultural development, increased cross-border activity including border security infrastructure development in their preferred habitat, and long-term climate change. However, the 2015 survey revealed major increases in population size to "record" levels, indicating that this ant population has not responded negatively to these anthropogenic challenges. Other factors such as year-to-year variation in summer rainfall and predation intensity probably control major long-term population size fluctuations at Organ Pipe.

Key words
Atta mexicana, environmental impacts, leafcutter ants, natural history, Organ Pipe Cactus National Monument, population size, population transect studies, Sonoran Desert

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Figure 2. A ranger-naturalist conducts an "ant walk" near the park visitor center (1987).

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Figure 3. *Atta mexicana* colony found by NPS staff in Lost Cabin basin (1980).

ment since the 1970s. Staff encountered one colony along the west side of the vehicle maintenance yard in the mid-1970s, and found a second in Lost Cabin basin (fig. 3).

I first encountered this species in the Sonoran Desert in northern Mexico in the 1970s. My initial interest was in foraging behavior of this ant in a desert habitat, which had not been previously described. A short natural history report (Mintzer 1979) led to initial contact with the Division of Resource Management at Organ Pipe and preliminary visits to the monument in 1980 and 1984. After the 1984 visit, resource management staff encouraged me to undertake a systematic survey. Their knowledge about colonies in the backcountry was nonexistent and indicated a clear need for a systematic survey in the park for this species to assess its population size, distribution, basic life history traits, and status. I wanted to identify several colonies in undisturbed settings that could be used for long-term study of diet, spatial pattern of foraging, and reproductive behavior. I conducted the first survey in December 1985.

Natural history of *A. mexicana*

From their central nest that may cover up to 20 × 20 m (66 × 66 ft), colonies access an annual foraging range that may exceed 2 hectares (5 acres), using a system of lateral tunnels that extend up to 130 m (427 ft) from the nest. The workers range in size from "minims" 2 mm (~1/16 in) long to "soldiers" 12 mm (~½ in) long. The female (queen) is the largest North American ant known, with a weight of about 500 mg (0.02 oz) and a body length of 20–22 mm (~3/4–7/8 in) (fig. 4, page 34). In the course of a year, established colonies may collect about 200 kg (441 lb) (dry weight) of leaf and


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Figure 4. Winged female (alate) reproductive of *Atta mexicana*.

flower material (Mintzer 1989, 1994). All of this forage becomes substrate for the growth of the ant's unique symbiotic fungus, cultured in large chambers deep underground under conditions of near-constant temperature and humidity. This growing fungus is the sole food source for the adults and larvae inside the nest (Weber 1972). After about a month, the fungus uses up available nutrients in the plant substrate, and the workers remove this old, exhausted fungus as waste and deposit it in large, distinctive "dump" piles on the soil surface above the central nest.

Successful reproduction of *A. mexicana* depends upon synchronized swarming of winged reproductive (alate) ants (Mintzer 2014). Alate ants are reared every spring by mature colonies, and disperse from them with predictably precise timing in predawn darkness to mate on the morning after summer (monsoonal) storms that deliver >1 cm (0.4 in) of rainfall. Newly mated queens remove their wings and attempt to excavate a vertical burrow to escape predation and daytime heat and desiccation (Mintzer et al. 1990; Moser 1967). New colony foundation (production of the first worker offspring) requires 1–2 months (Mintzer et al. 1990; Moser 1967; Weber 1972).

Methods

I analyzed high-resolution aerial photographs taken for Resource Management in 1976, to identify 11 large arroyo channel systems (fig. 5) in the southern one-third of the national monument with abundant vegetation to provide suitable habitat (Mintzer 1979) for these ants. I established these arroyos as transects for the repeat surveys and numbered them 1 through 11. I recruited a diverse group to assist with field searches: undergraduate and graduate student assistants, National Park Service staff, Volunteers in Parks program participants, and other motivated visitors and volunteers. Field searches employed 2–10 people spread laterally across the various banks and channels of each arroyo system; we walked the arroyo transects during daylight hours (9 a.m.–5 p.m.) when ant foraging activity was conspicuous in December or January. In addition, we noted any colonies found along the South Boundary Road extending ESE from Lukeville that provided access by vehicle to hike-in points for arroyo transects 9–11.

For each colony found, we recorded the location of the nest center in relation to the nearest arroyo channel, and any associated vegetative cover. Approximate age of individual colonies was

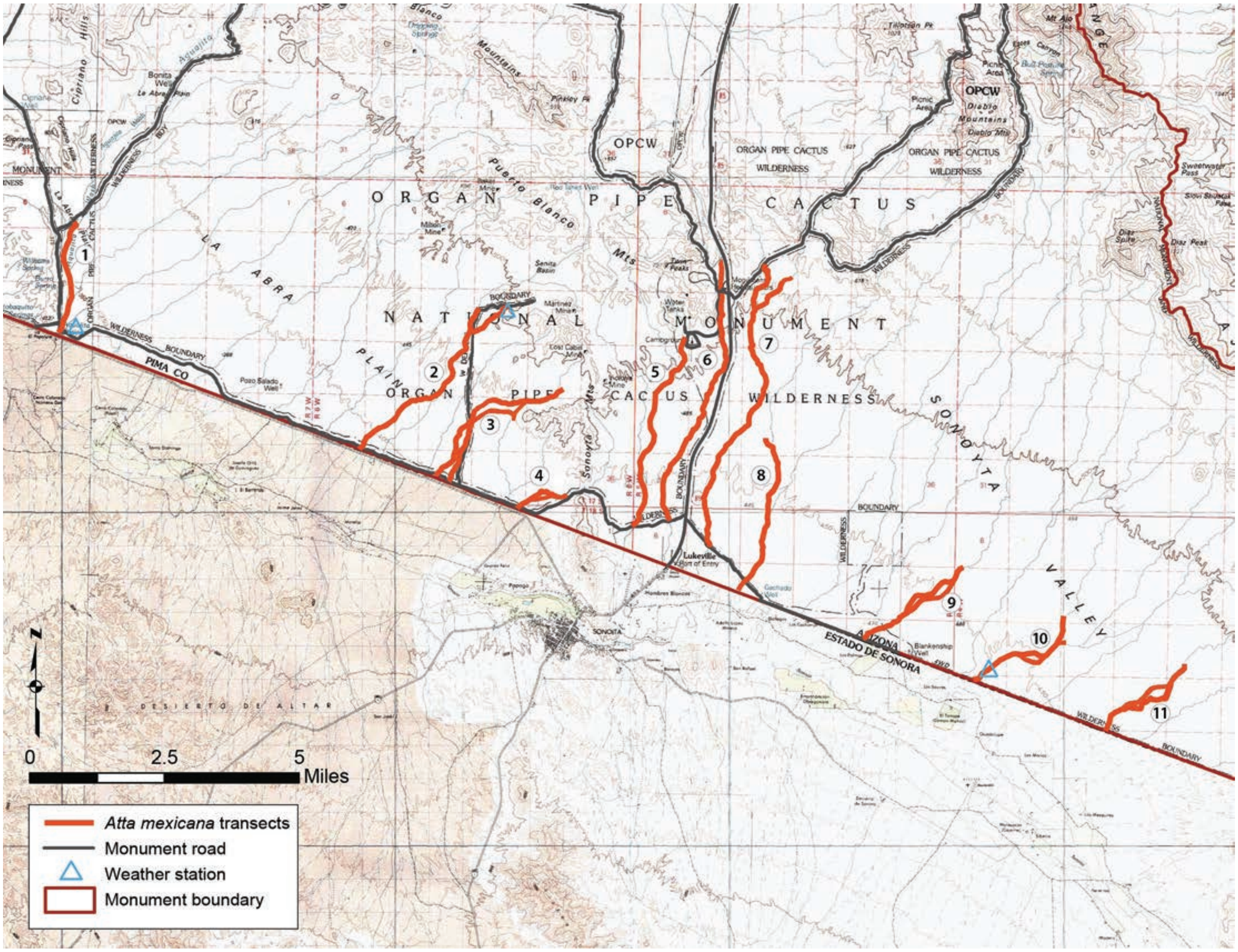

Figure 5. Map of the 11 arroyo survey transects (highlighted and numbered) along the southern border of Organ Pipe Cactus National Monument. Triangles show locations of weather stations referenced in text.

inferred from the size and condition of superficial accumulations of excavated soil above the central nest: young colonies (see fig. 1) have fewer nest craters and smaller fungal dump deposits than middle-aged, mature nests. Growing colonies have extensive accumulations of excavated soil in neat, sharp-edged craters above their centers (figs. 1 and 6, page 36). As colonies age past maturity, the surface earthworks begin to erode away, even as the fungal dump volume and surface area continue to grow. For very old colonies, the earthworks may be completely absent (fig. 7, page 36).

The first survey was conducted in December 1985; in this pre-Global Positioning System (GPS) era, the aerial photographs proved invaluable in the field to pinpoint and map colony locations along the unique twists and braids of each channel system. In November 1986, most of these colonies were revisited and tagged with aluminum labels wired to steel rebar stakes.

Ten years later, Resource Management at Organ Pipe supported my proposal to resurvey the arroyo transects to update knowledge of ant colony distribution, population size, and life span. In January 1996, we resurveyed the park population of *A. mexicana* and again walked all the arroyo channel transects searched in the original 1985 survey. Although aerial photographs were again used to navigate and pinpoint colony locations, we did not physically tag the colonies located in 1996. Instead, we documented location coordinates (>150 seconds duration, with a handheld GPS instrument) as close to the colony center as possible. We used a metal detector to attempt to relocate rebar-staked tags placed at colonies, which were often concealed by silt and debris deposited by flooding events or vegetative growth in the intervening 10 years. Although it was often impossible to relocate these tags, detailed locational information from the 1985 survey and the aerial photographs allowed us to ascertain colony locations without much

Figure 6. Center of mature colony (5–7 years old) along the US-Mexico border; view looking west (1985).

Figure 7. Same colony as in fig. 6; view looking east (2005). The earthworks are eroded flat and the fungal waste pile is prominent.

difficulty. In late December 2005 and early January 2006, we surveyed all the arroyo channel transects again. As in 1996, we took GPS readings as close to the colony center as possible. Finally, we surveyed the arroyo transects for a fourth time, in late December 2015 and early January 2016, using GPS field instruments. We organized the GPS readings from each day's survey into data files and added them to the park GIS databases.

Results

Table 1 provides an overview of survey results by arroyo channel transect. All 11 arroyo transects provided satisfactory habitat and hosted colonies at some point over the 30-year study period. During visits between survey periods, I also verified visitor and staff reports of backcountry colonies encountered in other parts of the park: an extinct nest along the Cuerda de Leña Wash, 2 km (1.2 mi) south of the north boundary (1987); a local cluster (deme) of four colonies in the Kuakatch wash system in the northeastern corner of the park (1989), close to the Tohono O'odham Reservation boundary; a colony near Bonita Well on the Puerto Blanco Drive and another near the first part of the Ajo Mountain Drive (early 1990s); a colony on the western park boundary (1999); a 22 km (14 mi) ground search in January 1994 along the Cherioni Wash from Highway 85 to Bates Well through the center of the park revealed only one new colony (1 km [0.6 mi] west of the highway) and no evidence of extinct nests.

1985 survey

We identified 35 living colonies in December 1985, and added two more large colonies in March 1987 along a 1 km (0.6 mi) extension of arroyo transect 6 north of the visitor center (Mintzer 1987 and 1988); this transect extension was included in all subsequent surveys.

Table 1. Number of *Atta mexicana* colonies found along 11 arroyo transects during four surveys in the southern part of Organ Pipe Cactus National Monument, Arizona

Arroyo/ Transect	Survey Periods			
	1985–1986	1995–1996	2005–2006	2015–2016
1	0	0	0	3
2	0	1	0	0
3	1	1	0	1
4	0	0	0	2
5	0	1	2	0
6	6	8	4	2
7	7	8	6	8
8	2	3	2	3
9	0	4	3	21
10	12	11	6	28
11	8	8	2	15
Total	36	45	25	83

Notes: Transects are listed west to east. "Off transect" colonies along or near the international boundary not associated with these 11 transects are excluded from the totals.

1995–1996 survey

We located 46 living colonies along the arroyo transects in the park; one additional colony was found in the US Customs and Border Patrol inholding at Lukeville. We found colonies in seven arroyo systems and in floodplains in Senita and Lost Cabin basins. All six transects with living colonies in the December 1985 survey still had colonies in January 1996; we also found colonies along three transects that lacked colonies in 1985.

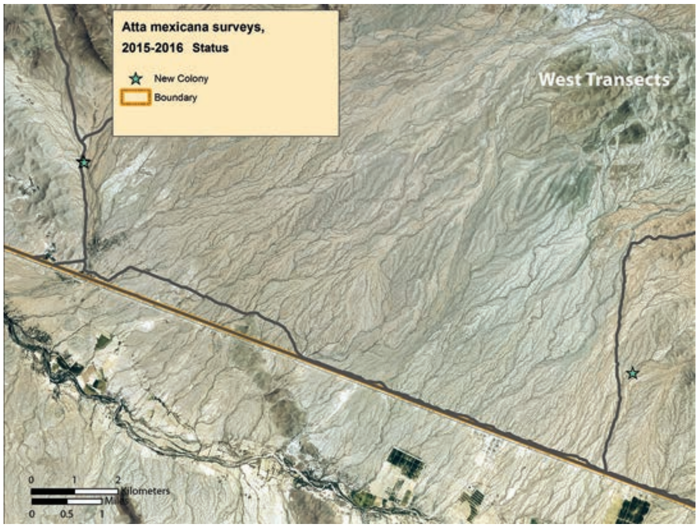

Figure 8. Map of colonies found along the western arroyo transects 1–3.

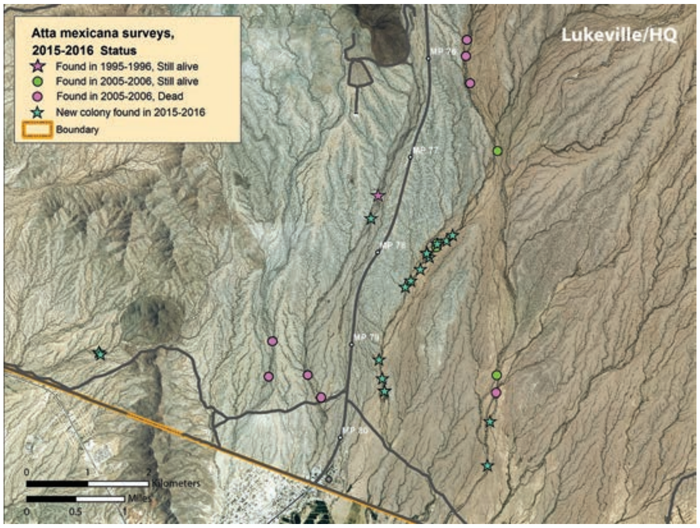

Figure 9. Map of colonies found along arroyo transects 4–8 in proximity to park headquarters, Lukeville, and Highway 85.

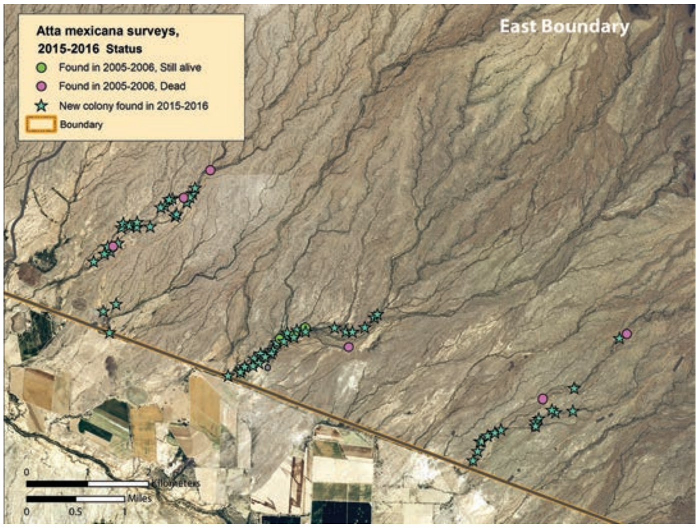

Figure 10. Map of colonies found along the eastern arroyo transects 9–11, east-southeast of Lukeville.

2005–2006 survey

This resurvey revealed little successful new colony recruitment and significant colony mortality over the previous 10 years. We found 25 living colonies along the transects, and one colony in Lukeville. Only four or five colonies first located in 1985 were still alive in 2005–2006, indicating that typical field colony life span is less than 20 years. We noted a substantial decline of populations west of Highway 85. We did not find any new colonies in the deme near monument headquarters, and only one colony in this area was still alive in January 2006. Unlike in previous surveys, we observed few younger colonies, and surviving colonies appeared older.

2015–2016 survey

We noted a slight population size increase in arroyo transects 1–6 to the west of Highway 85, and a major population increase in transects 7–11 east of the highway (figs. 8–10). For the first time, we found colonies in transects 1 and 4. At least nine colonies noted in 2006 were still extant in 2016, but the great majority of colonies were younger than 10 years, and most were 1–2 or 7–10 years old (table 2, page 38). In the three easternmost transects, the local density of colonies was higher than previously seen; some nests were only 30–40 m (33–44 yd) apart (fig. 10), rather than the typical 75–200 m (82–219 yd) as noted in previous surveys.

Discussion and conclusions

The *A. mexicana* population at Organ Pipe Cactus National Monument does not exist in a steady state: 30 years of data suggest major population size fluctuations over time (table 1). The overall spatial pattern that emerged from the four arroyo transect surveys reveals several widely scattered local clusters (subpopulations or demes) of colonies, with isolated outlier colonies as remnants of old demes undergoing local extinction, and the formation of new demes under favorable conditions (Mintzer and Mintzer 1988; Mintzer 1997, 2006).

Mean colony lifespan estimates of 10–20 years proposed in transect resurvey reports (Mintzer 1997, 2006) are consistent with estimates for other *Atta* species in the field and in captivity (see Weber 1972). Several *A. mexicana* colonies have survived at the national monument for more than 20 years, but none has survived over the complete 30-year survey period from 1985 to 2016. The deme along the northern part of arroyo system (transect) 6 near

Table 2. Number of *Atta mexicana* colonies with estimated colony age found along 11 arroyo transects during the 2015–2016 survey at Organ Pipe Cactus National Monument, Arizona

Arroyo/Transect	Estimated Colony Age (Years)					Total
	1–2	2–5	5–7	7–10	>10	
1	0	3	0	0	0	3
2	0	0	0	0	0	0
3	0	0	1	0	0	1
4	0	0	0	2	0	2
5	0	0	0	0	0	0
6	1	0	0	0	1	2
7	0	1	1	2	4	8
8	2	0	0	0	1	3
9	3	5	4	6	3	21
10	7	4	5	8	3	28
11	5	3	2	3	0	15
Total	18	16	13	21	12	83

Notes: Transects are listed west to east. "Off transect" colonies along or near the international boundary not associated with these 11 transects are excluded from the totals.

park headquarters has been followed most closely since the first survey; all five colonies present in 1987 were still alive 10 years later, but only one survived until December 2005 and it died out by October 2007. Overall, only 9 of the 26 colonies found in 2005 were still alive in 2015. At Organ Pipe, colony migration (where a colony disappearance is associated with appearance of another colony 50–200 m away) is rare; I found colonies remained in the same place during visits between the decadal surveys.

A. mexicana clearly fits within the large and growing assemblage of Sonoran plant and animal species that maintain populations with successful reproduction only in certain favorable years, and little to no success in many or most other years. Although this ant's reproductive success varies greatly from year to year, the species has responded very positively to conditions they encountered at Organ Pipe in recent years. Population recruitment since 2005 along arroyo systems 7, 9, 10, and 11 to the east of Highway 85 is striking (figs. 9 and 10). The majority of these colonies appear to be less than seven years old, and they occur in denser local aggregations than noted in the same areas in previous surveys. The population sizes along 8 of the 11 arroyo survey transects have increased over the past 10 years, and the short-term survival outlook for the Organ Pipe population has never been more favorable.

Management implications

To a great extent, Organ Pipe Cactus National Monument has been affected by external environmental factors over the past 30 years (NPS 2013, 2016). Agricultural development, road expansion, and urbanization in the area around Sonoyta, Mexico, immediately south of the park increased greatly between 1985 and 2005 and continue to this day, threatening monument ecosystems through habitat isolation, nighttime illumination, groundwater depletion, pesticide drift, woodcutting, and invasive species facilitation (NPS 2013). Major increases in cross-border violations during this period led to an equal interdiction response by law enforcement. This included major additions to border security physical infrastructure after 2006, such as a vehicle barrier along most of the border and a 5.2-mile- (8.4 km) long pedestrian fence (NPS 2013, 2016). Additionally, long-term climate change models forecast more frequent and intense droughts in the Sonoran Desert (NPS 2016), potentially having an impact on *A. mexicana* and its host plant community. These anthropogenic disturbances act in concert with other biotic and abiotic factors. All of these elements have concerned resource managers at the monument for decades and led to the selection of several long-term research sites adjacent to the international park boundary in order to measure ecological changes (Bennett and Kunzman 1987; Brown 1991; NPS 1995). How these factors affect population survival and recruitment of this leafcutter ant species at Organ Pipe and thereby drive long-term changes in population size is considered in the following paragraphs in order from most to least significant.

Table 3. Number of summer rainfall events for 20 years at three Organ Pipe weather stations

Calendar Year	Rainfall Events by Location								
	Aguajita Wash			Senita Basin			Salsola		
	≥ 1 cm	≥ 1 in	Max (in)	≥ 1 cm	≥ 1 in	Max (in)	≥ 1 cm	≥ 1 in	Max (in)
1995	ND	ND	ND	3	1	1.11	6[a]	2[a]	2.39[a]
1996	3	1	1.09	4	1	1.21	6[a]	2[a]	2.45[a]
1997	1[b]	0[b]	0.70[b]	3	0	0.76	5[a]	1[a]	1.01[a]
1998	0[c]	0[c]	0.26[c]	3	0	0.85	4	2	1.54
1999	ND	ND	ND	3	0	0.78	6[a]	0[a]	0.91[a]
2000	ND	ND	ND	3	0	0.79	4	0	0.85
2001	ND	ND	ND	4	0	0.75	2	1	1.23
2002	0[c]	0[c]	0.15[c]	0[c]	0[c]	0.25[c]	2[b]	0[b]	0.46[b]
2003	6[a]	2[a]	1.87[a]	4	3	2.11	5[a]	2[a]	1.48[a]
2004	ND	ND	ND	2[b]	0[b]	0.92[b]	1[b]	0[b]	0.93[b]
2005	2	1	1.32	3	1	1.15	1[b]	0[b]	0.59[b]
2006	3	0	0.74	2[b]	0[b]	0.60[b]	5[a]	1[a]	1.70[a]
2007	1	1	2.33	2[b]	0[b]	0.79[b]	0[c]	0[c]	0.35[c]
2008	1	1	1.28	ND	ND	ND	4	2	2.06
2009	1[b]	0[b]	0.49[b]	0?	0?	ND	1[b]	0[b]	0.78[b]
2010	ND	ND	ND	1	1	1.14	1[b]	0[b]	0.65[b]
2011	ND	ND	ND	0[c]	0[c]	0.39[c]	3	1	2.82
2012	7[a]	4[a]	1.50[a]	6[a]	1[a]	1.08[a]	8[a]	0[a]	0.92[a]
2013	3	1	1.39	3	1	1.23	5[a]	1[a]	3.92[a]
2014	2[b]	0[b]	0.80[b]	3	0	0.76	5[a]	1[a]	1.75[a]
Cumulative	28	10		33	7		46	10	

Note: Rainfall events are from daily records over four months from June through September. Maximum daily rainfall is shown during these periods. Cumulative counts (last row) only include 11 years when comparable complete records are available for all three stations.

ND indicates station records with missing data.

[a]Green denotes wetter years.

[b]Brown signifies drier years.

[c]Red indicates the driest years.

1. Year-to-year cycles in summer precipitation. Like other *Atta* species (Moser 1967; Weber 1972), *A. mexicana* colonies at Organ Pipe do not release all their alate ants on a single night of swarming; a large number are held back for one or more subsequent nights. After heavy (5 cm [2.0 in]) rains, swarming may occur over at least two nights consecutively; after lighter rains, colonies may swarm just once and then await additional rain events over the next few weeks. While distribution of reproductive activity over multiple nights of swarming may be adaptive in habitats receiving more regular and frequent summer rains (i.e., in southern Sonora and the rest of Mexico), it carries unique risks in the Sonoran Desert.

Although monsoonal storms occur every summer at Organ Pipe, their frequency and quality vary greatly from year to year and from place to place. Since the late 1980s, the national monument's resource management staff has accumulated daily precipitation data records from three field stations most relevant to the ant population: Aguajita to the west, Senita Basin in the center, and Salsola to the east (fig. 5). Table 3 shows the number of significant (≥1 cm and ≥1 in) summer rainfall events (June through September) recorded at these weather stations from 1995 through 2014. During at least 2 of these 20 years at Aguajita (1998 and 2002) and Senita Basin (2002 and 2011) and 1 year (2007) at Salsola, inadequate summer monsoon activity (shown in red and so noted in table 3) almost certainly prevented any swarming. For the 11 years with complete and comparable data for all three stations, no geographic west-east trend is seen for 1-inch threshold events, but the number of 1 cm (0.4 in) threshold events increased 64% from the western station (Aguajita) to the eastern station (Salsola). Not every 1 cm rain is followed by swarming; early morning (midnight to 4 a.m.) rainfall or breezes will inhibit predawn swarming, and daytime heat after modest morning rainfall may dry the soil surface and prevent swarming the following night. Thus, tabulation of 1 cm events probably overestimates the number of reproductive episodes. The 1-inch (2.5 cm) threshold, however, indicates events of higher quality that are more likely to trigger swarming over the following night or two.

Successful reproduction and population recruitment of new colonies appear to be associated with summers with more rain events, heavier maximum rain events, or both. Such summers provide leafcutter ant colonies with ample opportunities to deploy all or nearly all of their alates and maximize their reproductive success. Newly founded nests may survive the late summer and fall best in wet years. The Salsola weather station is located within arroyo transect 10, which had more *Atta* colonies than any other transect during three of the four surveys (and tied with transect 7 for most colonies in the 2005–2006 survey; see table 1). Salsola also provides an uninterrupted daily rainfall record over 20 years (1995–2014; table 3). Over the 10-year period 2005–2014, six years (2006, 2008, 2011, 2012, 2013, and 2014) delivered above-average frequency of 1 cm threshold events, heavier maximum rainfall events, or both. The age data (table 2) for transect 10 show a diverse range of colony ages, indicating successful reproduction during multiple "good" years spread throughout the decade, although it is not possible to ascribe origins of any specific colony to a particular rain event.

2. Anthropogenic climate change probably is an important factor, especially for the long-term future. These ants are living at their limits of tolerance for arid conditions. The American Southwest in general has experienced more frequent drought conditions in recent decades. Consensus climate change models forecast intensification of this trend this century (NPS 2016). The timing and quantity of summer and winter rainfall determine the health of host plants of the ant and the availability of foliage, flowers, and fruits for harvest. In the Sonoran Desert, *A. mexicana* colonies along arroyo channel margins have access to a mix of important host plants: larger trees such as palo verde (*Cercidium* spp. and *Parkinsonia* spp.), ironwood (*Olneya* spp.), mesquite (*Prosopis* spp.), and catclaw (*Acacia* spp.) along the channels, and creosotebush (*Larrea* spp.) in the open desert away from these channels. The ants depend upon these plants throughout the year. In addition, increased shade and soil moisture along arroyo channels is probably vital for new colony foundation and population recruitment. Along the western transects, diversity and coverage of larger trees (except *Prosopis*) is reduced, and abundant saltbush/bursage (*Franseria* spp./*Ambrosia* spp.) populations reduce the density of *Larrea* in the open desert. *A. mexicana* populations are smaller and more isolated in the western transects at Organ Pipe, which experience lower mean annual rainfall. For the 11 most recent years with complete and comparable data, mean annual rainfall was 6.09 ± 2.51 inches (15.47 ± 6.38 cm) at Aguajita (at the western edge of the survey area), 7.22 ± 2.82 inches (18.34 ± 7.16 cm) at Senita Basin, and 9.02 ± 2.70 inches (22.91 ± 6.85 cm) at Salsola along densely populated arroyo transect 10 to the east. Extended drought conditions that eliminate threshold (1 cm [0.4 in]) monsoonal rainfall events over a decade or more would prevent swarming activity, prevent successful colony establishment, and lead to decline or extinction of local populations. Sadly, *A. mexicana* should be a good indicator species for effects of sustained severe drought at Organ Pipe.

Several A. mexicana *colonies have survived at the national monument for more than 20 years, but none has survived over the complete 30-year survey period from 1985 to 2016.*

3. Inferred potential decreases in local populations or effectiveness of natural alate ant predators, particularly bats, nighthawks, and Colorado River toads. The large size and innocuous nature of alate *A. mexicana* males and females make them attractive food items for local nocturnal and crepuscular (dawn-active) insectivores, and it was easy to observe predation by bats and toads associated with predawn swarming activity in 1986, 1987, 1989, and 1997 at Organ Pipe. Even though *Atta* alates are a rare food resource, available in abundance only a few nights a year and in very limited areas, bats were seen circling and gleaning alates on the ground and those taking flight from swarming colonies. Nighthawks are also common at Organ Pipe and are a known predator of alates of other *Atta* species (Moser 1967). Other opportunistic mammalian predators that may seek alates and young colonies at Organ Pipe include the American badger and spotted skunks; armadillos, observed to feed on *A. texana* in Louisiana (Moser 1967), are absent in Arizona.

Comparison of Salsola rainfall data (1995–2004 versus 2005–2014 in table 3) does not show a convincing decadal trend to explain overall increased reproductive success since 2005, so we must consider alternative explanations. The more recent surge in number of colonies in transects 9–11 near Salsola suggests that predator pressure on this local ant subpopulation may have decreased. This could be due to reduced predator population sizes, changes in predator foraging behavior, or temporary satiation of local predators associated with dense *Atta* swarms.

A. mexicana clearly fits within the large and growing assemblage of Sonoran plant and animal species that maintain populations with successful reproduction only in certain favorable years, and little to no success in many or most other years.

4. Increased human population and agricultural land use in Sonoyta, Mexico, adjacent to the national monument could isolate Organ Pipe populations of *A. mexicana* from source populations to the south, but this did not prevent vigorous colony reproduction and population recruitment over the last four years. These numerous younger colonies were almost certainly founded by females originating locally from the few surviving mature colonies in Organ Pipe or from colonies within a few kilometers of the international boundary. Clearance of land for agriculture that isolates park populations of *A. mexicana* from source populations in Mexico would have long-term effects on genetic diversity. The alates are not strong fliers and only swarm on calm nights; dispersal distances of winged reproductive *Atta* females are probably less than 5 km (3.1 mi) (Moser 1967). Very slight airflow from the southeast associated with monsoonal conditions may have had a role in moving some alate females from borderland Sonora into Organ Pipe.

There is no evidence so far suggesting that pesticide drift and groundwater depletion associated with intensive agriculture have affected host plants and ant populations near the international boundary. Cutting of *Olneya* and *Prosopis* trees in riparian habitats near the boundary could also have an effect. Because alate ants are attracted to lights, nighttime illumination will affect dispersal of some winged reproductive ants during predawn hours. However, these ants continue to thrive in well-lighted, urbanized areas in central and coastal Mexico, so this also may be a minor concern.

5. Increased border security infrastructure has the potential to amplify effects outlined in the factor above. Construction of a vehicle barrier along the international boundary began in 2003, but the limited vegetation clearance and 2-meter- (6.6 ft) deep posthole excavation associated with it have not had a major impact on colonies along the southern monument boundary. However, construction of the 18-foot pedestrian barrier (fence), widening of roads, and installation of high-intensity nighttime illumination along limited areas of the border began in 2007, and this infrastructure could have a negative effect on *A. mexicana* populations at Organ Pipe. Also, the use of all-terrain vehicles to interdict cross-border violators has produced visible local degradation of near-border plant communities (NPS 2013), although the effects on colony survival may be minimal for reasons outlined in the fourth factor above.

6. Cross-border activity is another factor. This activity increased significantly between 1985 and 2005 at Organ Pipe (NPS 2013), and was often concentrated along the large arroyo channel systems that are preferred habitat of *A. mexicana* in the Sonoran Desert. Since 2008, cross-border violations have decreased significantly, though certain routes, like arroyos, tend to be used with some frequency and routes change often in response to interdiction (NPS, T. Tibbitts, resource management specialist, personal conversation, April 2012). Transient pedestrian traffic probably has negligible effects on ant foraging behavior, and accumulation of trash probably has no effect on established colonies. Cross-border violators often break off lower branches to open up sheltering spaces under some larger trees along arroyos, but as long as these large host trees (*Parkinsonia*, *Cercidium*, *Olneya*, *Prosopis*, *Acacia*) are not seriously damaged by transient activity, this impact will be minor; in any case, the deep nests are highly resistant to local disturbance.

Conclusion

Atta mexicana is a charismatic invertebrate with complex social behavior and fascinating natural history, living at the limits of its tolerance for aridity and temperature extremes. Like other such species surviving at the margins of their range, it should be a sensitive indicator for long-term environmental impacts. Although Resource Management has not yet included this ant in its long-term monitoring program, its support for decadal surveys is likely to continue. Finally, an effort should be made to integrate molecular genetics technology with future study of this park population to assess inbreeding, genetic diversity levels (always a concern in small, isolated populations), gene flow (effective dispersal), colony genetic structure (number of queens per colony), and to estimate effective population size.

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Impact of sample frame on survey response rates in repeat-contact mail surveys

By Chris Neher and K. S. Neher

Abstract
From December 2015 to January 2016, researchers from the University of Montana in Missoula conducted mail surveys of six different sample populations nearly simultaneously. The result is a unique opportunity to compare the characteristics of the populations being sampled so as to draw conclusions about the importance of various factors in determining response rates. The researchers found that age, issue familiarity, sampling targeted populations, and the uniqueness of the experience being studied all have an impact on the rate of response.

Key words
Dillman method, mail survey, National Park Service, response rate

AN INTEGRAL PART OF MANY STUDIES CONDUCTED for the National Park Service (NPS) by either outside contracted professionals or by NPS staff is survey research. These surveys range from small focus groups or cognitive interviews to large-scale national household surveys. They differ in content, targeted population, length, and survey methodology. However, when surveys involve contacts with 10 or more members of the public, they all have one thing in common: the need to secure Office of Management and Budget (OMB) approval of the survey instrument and study design prior to conducting the research. As part of preparing an information collection request (ICR) package for submission to OMB, researchers are asked to state the sample sizes and estimated response rates for their survey. Survey research faces an increasing challenge because of generally declining survey response rates (Keeter et al. 2017; AAPOR 2016). In this climate, it can be a bit like tossing darts to estimate response rates for surveys not yet completed, especially if the target survey population is not one that is frequently surveyed.

From December 2015 to January 2016, researchers from the University of Montana in Missoula conducted a wide range of mail surveys for research projects sponsored by the National Park Service and the US Geological Survey. Due to a fluke of gaining OMB approval for three different information collection programs within two months of each other in the fall of 2015, we were able to conduct mail surveys of six different sample populations nearly simultaneously. As the studies had all been designed by the same research team, the surveys were conducted using identical Dillman (2007) repeat-contact mail protocols along with identical mail packaging and postage applications. Survey contents, length, and complexity varied somewhat; however, because so many aspects of these surveys were parallel, we had the special opportunity to compare response rates across very different sample populations while controlling for many factors that might affect those rates. Rather than providing a statistical analysis of factors influencing mail survey response rates, our analysis is limited to a side-by-side comparison of response rates, made possible by the coincidence of six mail surveys being conducted simultaneously. The goal of this article is to provide recent benchmarks for researchers designing mail surveys to inform their a priori or presumptive judgment of likely response rates based on general factors of the population being surveyed.

Recent trends in survey response rates

The Pew Research Center reported their rates of response to telephone surveys dropped from 36% in 1997 to 9% in 2012. In more recent years that response rate has been found to stabilize at 9% (Keeter et al. 2017). Although in the Pew study the method of data collection (phone calls) was different from that employed by the studies described in this article (mail-back surveys), it is indicative of a wider trend. The American Association for Public Opinion Research (AAPOR) notes that "[l]argely due to increasing refusals, response rates across all modes of survey administration have declined, in some cases precipitously" (2016).

For a given survey, response rate is dependent on a wide range of interrelated factors, the relative importance of which change from individual to individual (Heberlein and Baumgartner 1978). The leverage-saliency theory of survey participation proposes that no single method has been shown to universally increase response rates because no single influencing factor holds constant in the magnitude of its influence across survey populations, and further that "the effect of one factor may be altered in the presence of another" (Groves et al. 2000). As such, there is no magic bullet for low or declining response rates, but certain methods have been consistently, if not universally, shown to be effective in increasing participation. One such method is the Dillman protocol employed by the studies discussed in this article (Chidlow et al. 2015).

Table 1. Mail survey populations, sample frames, and response rates

Population	Sample Frame	Response Rate
Private Grand Canyon whitewater floaters	Random sample of all floaters in calendar year 2015	64.3%
National Parks and Federal Recreational Lands Pass Senior Pass holders	Random sample of most recent 12 months of online purchasers	63.3%
Glen Canyon anglers	On-site recruitment of anglers near Lee's Ferry	56.9%
National Parks and Federal Recreational Lands Pass Annual Pass holders	Random sample of most recent 12 months of online purchasers	43.5%
Households in eight counties surrounding the Colorado River	Random address-based sample (ABS) of households in eight-county Colorado River area	17.6%
National households	Random ABS of US households	11.7%

The most substantial threat posed by lower rates of participation is the possibility of nonresponse bias, which occurs when the data collected are not representative of the population surveyed because of a higher rate of nonresponse among segments of the population whose answers would have differed systematically from those collected. For example, a common type of nonresponse bias is that of age: older individuals are generally more likely to respond to a survey, so younger people can be underrepresented in the data. In the past, a high response rate was considered the most important safeguard against nonresponse bias, and surveys with low rates of participation were thought to be necessarily unreliable. Recent studies, however, have shown that lower response rates are not inherently correlated with a higher incidence of nonresponse bias (Keeter et al. 2000; AAPOR 2016; Keeter et al. 2017). Furthermore, bias that is known to exist in a study can be corrected for through monitoring and weighting of key demographic factors among the respondents. This goes to show the decline in survey participation has not undermined the reliability of surveys as a method of statistical prediction; rather it has demonstrated the effectiveness of statistical research best practices (Keeter et al. 2000).

Survey and sample frame characteristics

In September and October 2015, OMB approved three ICR packages that had been submitted by University of Montana

The survey explored issues specific to the Colorado River ecosystem and the operation of Glen Canyon Dam with sampling of the rafting public and river anglers.

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researchers for studies either entirely or partially funded by the National Park Service. These studies included survey designs for six different sample populations (table 1). The Glen Canyon Total Valuation Survey (Duffield et al. 2016a) was designed to sample two populations: a random address-based sample (ABS) of national households and a household sample of eight counties contiguous with the Colorado River from Lake Powell to Lake Mead (also a random ABS). A second study was designed to survey holders of National Parks and Federal Recreational Lands Passes (Neher 2016a, 2016b). Specifically we sampled pass purchasers who bought their passes through the USGS website portal. Again, this involved two randomly sampled populations: purchasers of the Annual Pass and purchasers of the Senior Pass. A final study of direct recreational users of the Colorado River corridor from Glen Canyon Dam downstream to Lake Mead (Duffield et al. 2016b) was funded in phases by both the NPS and the USGS. This study surveyed two groups of river users: private whitewater floaters traveling through Grand Canyon and anglers fishing the river stretch from just below Lee's Ferry upstream to Glen Canyon Dam. Researchers randomly sampled Grand Canyon floaters from a listing of all private-party river floaters in the previous 12 months, while they contacted anglers on-site.

The survey protocol for all samples followed the Dillman repeat-contact method of (1) an advance notice postcard, (2) a full survey package with postage-paid return envelope, (3) a reminder postcard, and (4) a final full survey package sent to nonrespondents.

As is clear from table 1, the response rates from the six different sample frames differ dramatically, ranging from a low of 11.7% for the national household sample to a high of nearly 65% for the Grand Canyon whitewater floater sample. Consideration of the key population characteristics for the samples helps to inform factors that may drive response rates.

Results and discussion

Age matters

The two surveys of the America the Beautiful–National Parks and Federal Recreational Lands Pass holders were identical in most ways, including survey questions, source of sample, and methodology. The one key way these samples differed was in the age of the sample population. The *Annual Pass* survey returns had an average reported pass-holder age of 46 years. The *Senior Pass*, by contrast, has a minimum age of 62 years required to qualify for purchase and an average respondent age of 66. Given the similarity of the two sample frames and survey methods and contents, we were surprised at the significant increase (20 percentage points) in response rates achieved for the *Senior Pass* survey as compared with the *Annual Pass* survey. Survey researchers have recognized that when compared with younger population an older-age sample population is often associated with increased response rates (see, for example, Gigliotti and Dietsch 2014), and these surveys underline how significant those differences can be.

For household samples, issue familiarity matters

The household surveys associated with the Glen Canyon Total Value study included two sample frames: a random sample of national households and a sample of households in the eight counties contiguous to the Colorado River from Lake Powell to Lake Mead. The survey itself dealt with issues specific to the Colorado River ecosystem and the operation of Glen Canyon Dam. Survey responses indicated that while only 11.5% of respondents to the national survey reported having visited Glen Canyon Dam, 57.5% of the regional sample respondents had visited the dam. We reason that the higher level of familiarity of the regional respondents with the subject of the survey largely explains the higher response rate for the regional sample (17.6%) versus the national sample (11.7%).

Response from targeted user groups differs greatly from household sample response

Survey researchers have long been aware that surveys of people about their chosen activities have substantially higher response rates than general population surveys on issues many or most people may have little familiarity with or interest in (Heberlein and Baumgartner 1978). This finding is also clear in the final response rates of our differing surveys. The *highest* response rate for one of our two household samples (17.6%) is still lower than one-half as high as the *lowest* rate from our four targeted user samples (43.5%).

Among recreational users the uniqueness of the activity being surveyed matters

The surveys of Glen Canyon anglers and Grand Canyon whitewater floaters both had similar survey instruments asking the same groups of questions. However, the response rate for the whitewater sample was 10% higher than that for the angler sample. This was true even though we had contacted the anglers on-site and they had agreed to participate in the survey, as opposed to Grand Canyon floaters whom we sampled from among the entire population of floaters. Additionally, the average angler respondent was significantly older (56 years) than the average floater respondent (48 years).

One explanation for the higher response rates among floaters might be the nature of the experience being surveyed. Floating the Grand Canyon is a once-in-a-lifetime experience for many, and at most a once-per-year experience for all. In contrast, the respondents to the Glen Canyon angler survey had been fishing the site on average for 11 years, and made an average of 3.7 trips to Glen Canyon to fish each year. In short, the Grand Canyon whitewater experience, which generally lasts two weeks or longer, is likely a much more special and memorable experience than an average Glen Canyon fishing trip, which might last only one or two days. Additionally, based on the preponderance of survey response comments, a much greater share of Grand Canyon whitewater floaters than Glen Canyon anglers were excited about their recent Colorado River visit and were eager to tell survey researchers about that experience. That eagerness appears to have translated into a bolstered survey response rate.

Take-home lessons for survey researchers

The repeat-contact mail surveys that we have described provide researchers with a starting point for estimating what response rates they might expect in their similarly structured surveys. Additional methods could be applied to future similar studies to boost response rates:

- A web-based survey alternative response method could also be used
- Follow-up phone contacts to nonrespondents to urge them to participate[1]

With regard to the straightforward Dillman mail protocol used in these surveys, researchers should be mindful primarily of the level of attachment and interest their sample population has in the subject of the survey, and secondarily of the age of the respondent pool.

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1 A 2016 household survey (Haefele et al. 2016) used these additions to the repeat-contact protocol: a web-based response option and reminder telephone calls. The study additionally used a $2 incentive payment. The response rate for this national survey conducted by Colorado State University and Harvard University was 18%.

COURTESY OF JO ANN DOLLARD

Experimental reintroduction of state-endangered beach pea (*Lathyrus japonicus*) to Indiana Dunes National Lakeshore

Figure 1. The beach pea flower is compact and erect, its color a showy purple. Reintroduced beach pea grows only in areas where human disturbance and competition are minimal.

By John J. Dollard, Jr.

Abstract

Reintroduction of plants has become an increasingly important restoration tool as more natural landscapes are impacted by urban development. Beach pea (*Lathyrus japonicus*) is an early successional plant growing in foredunes throughout the Great Lakes, USA. This species is sensitive to trampling and heavy recreational use, and currently is endangered in Indiana. We reintroduced 350 plants into three locations at Indiana Dunes National Lakeshore in 2008. By the end of October of that year, 56 (16%) plants had survived. Supplemental watering, locations closer to the lake, and longer stem length were associated with higher rates of survival. Since those experimental reintroductions, we have grown and transplanted new individuals at the park, establishing a healthy population at the westernmost site where population numbers have grown, and pioneering another population at an eastern park site. Our best success with reintroductions has been with more mature transplants on lower foredunes. From the original 56 survivors of the 2008 experimental reintroduction, the population had increased tenfold.

Key words

beach pea (*Lathyrus japonicus*), foredune, Great Lakes, Indiana Dunes National Lakeshore, survival

BEACH PEA (*LATHYRUS JAPONICUS*), A STATE-LISTED endangered plant in Indiana, was once a common foredune plant along the coast of Indiana Dunes National Lakeshore (fig. 1). Although it is found throughout the Great Lakes, the species is extirpated at the park because of anthropogenic pressures. These include high recreational use, destruction of sand dunes by industry, construction of seawalls that obstruct the natural sand movement, and urban development.

The national lakeshore is located along the southern border of Lake Michigan, approximately 80 km (50 mi) east of Chicago, Illinois. The park is composed of 29 km (18 mi) of coastline and 5,754 ha (14,218 ac) of dune system, and a large interdunal wetland exists behind the coastal beach.

The park stands out as having the highest plant diversity of northeastern national parks (Hatfield et al. 2013; USGS, N. B. Pavlovic, research ecologist, e-mail, 20 February 2018). In the early 20th century, Henry Cowles of the University of Chicago conducted pioneering research on plant community succession. Cowles Bog, named in his honor, is now a large wetland restoration site located near the coast.

In preparation for reintroduction of beach pea to Indiana Dunes National Lakeshore, we visited several beach pea populations along the coasts of Lakes Michigan and Superior, including the only natural population of the species in Indiana and others at Sleeping Bear Dunes and Pictured Rocks National Lakeshores in Michigan, and Apostle Islands National Lakeshore in Wisconsin (fig. 2). We considered the beach pea populations at Sleeping Bear Dunes, Pictured Rock, and Apostle Islands to be reference populations, because they were not subject to human-caused environmental stresses or shoreline disturbance. At these locations we collected information on beach pea habitat, reproduction, and common plant associates.

In addition, we conducted a trial experiment in 2007 to evaluate possible reintroduction sites at Indiana Dunes and to understand the effects of winter storms on transplants. That same year, we built a raised wooden structure near the park's plant nursery, filled it with sand, and planted it with juvenile beach pea plants. The purpose of this was to provide seeds for future reintroduction work. We initiated the experimental beach pea reintroduction in 2008.

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Figure 2. Beach peas at Sleeping Bear Dunes National Lakeshore are surrounded by marram grass, a common plant associate.

Beach pea habitat and biology

Beach pea is an early successional plant that grows commonly on the foredune nearest the lake or ocean. Its geographic range is along the coast of North America, Europe, and Asia. The plant is now endangered in Indiana and extirpated in Illinois.

Beach pea is a glabrous (smooth) perennial with procumbent stems (that sprawl along the ground) (Brightmore and White 1963). Its leaves are slightly fleshy and pinnate (i.e., divided into leaflets), ending with a long tendril that acts as an anchor. Flowers are compact and erect unbranched stems, which bloom from June through August. From late summer to early fall, the plants form brown seedpods.

Beach pea often grows in open areas near the crests of foredunes, in locations with low wave energy. I have also observed that it grows in the coastal strand near water. We have found some populations growing in blowouts (interior areas where the foredune has been breached), farther back from the lake.

Although beach pea is a prolific seeder, the majority of plant reproduction is vegetative through rhizomes (underground stems) that can grow 1 m long (3.3 ft). Once seeds are dispersed by the plant, conditions have to be almost perfect for germination. New plants from seed might develop in a low, wet depression in the sand or around wrack (plant debris), which would provide the seed a moist environment.

In the more remote, less visited sites (Michigan and Wisconsin) along the first foredune, I observed marram grass (*Ammophila breviligulata*, see fig. 2) and Pitcher's thistle (*Cirsium pitcheri*) as common plant associates of beach pea. At Indiana Dunes each of these plants has been impacted by anthropogenic stressors. Beach pea is now extirpated and is state endangered. The only population in Indiana is located at a nearby natural preserve. Pitcher's thistle is federally listed, with small populations scattered in blowouts throughout the park. And marram grass, which still commonly grows along the foredunes, has been impacted by trampling in high recreational areas.

Experimental reintroduction

Horticultural methods

We collected seeds for the experimental reintroduction in 2007 from a population along the coast of Lake Michigan in Indiana. We placed the seeds in a cool location for drying and then cleaned them before storing them for winter. Seeds were cold stratified for three months. Then, the following spring (March 2008), we nicked with a knife a small section of each impermeable seed coat to expedite germination.

We planted the seeds in a growing medium comprising three parts sand and one part peat. Once seeds germinated and seedlings produced their first true leaves, we submerged the plants in a solution of inoculant (*Rhizobium leguminosarum*). This bacterium colonizes beach pea root nodules and forms a symbiotic relationship with the plant. It fixes nitrogen from the air, which acts as a nutrient to the plant. The seedlings are then transplanted

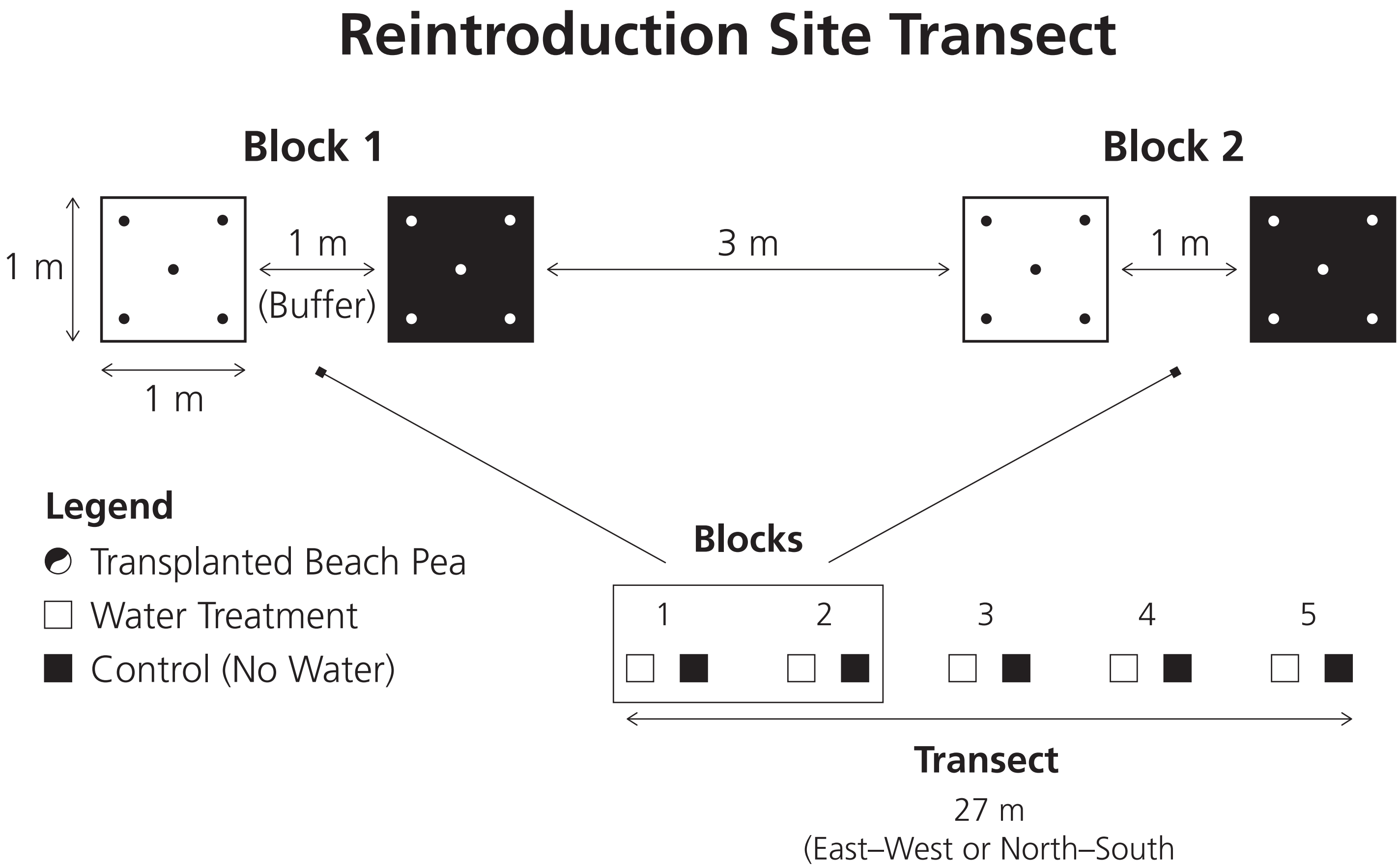

Figure 3. Each of the seven reintroduction transects was composed of five blocks of paired square-meter planting zones separated by buffers. Each block received 10 plants, half as controls that did not receive supplemental watering and half that did.

into larger containers. A heated greenhouse provided the growing environment for the plants until the last frost, at which time we moved them to an outdoor open shade house, to acclimate the seedlings for planting at the reintroduction site.

Experimental design and planting

In May 2008 we transplanted 350 beach pea seedlings at seven sites among three reintroduction locations at Indiana Dunes—East Site (four sites), Central Site (one site), and West Site (two sites). At each site we introduced 50 plants along a 27-meter- (89 ft) long transect (Dollard and Carrington 2013). Each site consisted of ten 1 m^2 (11 ft^2) quadrats, grouped into five treatment blocks with each block consisting of one quadrat with and one without supplemental watering. Five seedlings were planted in each quadrat (fig. 3). For quadrats receiving supplemental watering, we placed circular plastic plant collars (20 cm diameter, 17 cm deep [8 × 7 in]) around the transplants to help direct water to their bases (fig. 4). These quadrats were watered three times per week

Figure 4. Beach peas in the water treatment zones were ringed with plastic collars to help retain moisture. Pins marked with red flags allowed resource managers to measure sand erosion and accretion.

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Figure 5. The author applies supplemental water at one of seven reintroduction sites.

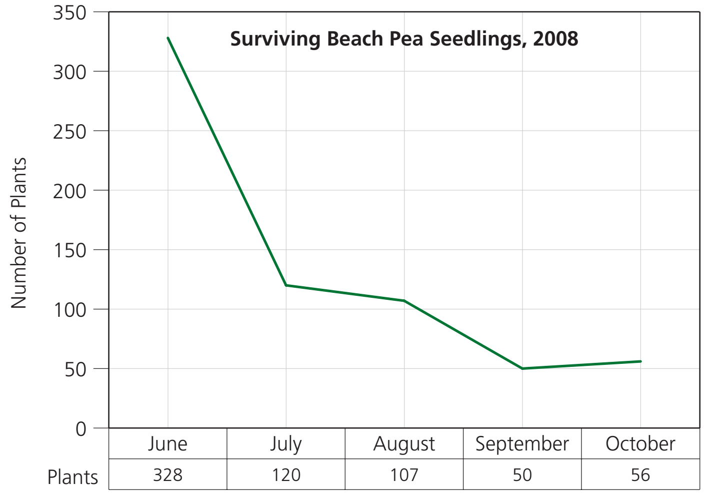

Figure 6. Beach pea survival stabilized at 50 plants by fall 2008. Subsequent transplanting operations take advantage of lessons learned from the experimental reintroduction to help boost survival. Tactics now involve the use of larger plants, transplanting in fall, and placing seedlings near nurse plants when feasible.

(2 liters lake water/1 m^2 [6 oz/1 ft^2]) from June through October (fig. 5).

We constructed a silt fence approximately 1 m (3 ft) high on the lake-facing side of all site transects, to alleviate possible sand accretion or erosion around seedlings. We placed five erosion pins (wooden dowels) measuring 1.2 m long by 1 cm diameter [3.9 ft × 0.7 in]) in each site behind and outside of the silt fence, to measure rates of sand accretion or erosion (see fig. 4).

Data collection

We recorded plant survival and stem length at monthly intervals through October 2008. We measured percentage of open canopy for each 1 m^2 (11 ft^2) quadrat during late summer of 2008. In addition, we recorded slope, aspect, and distance to the lake for each site. In spring of 2009, we took measurements on each erosion pin, recording sand accumulation and erosion.

From June to October, we measured percentage of soil moisture once a week in the center of each quadrat using time domain reflectometry (Mini Trase instrument). We installed four rain gauges (one at West Site, one at Central Site, and two at East Site) and made recordings once a week from June to October.

Statistical analysis

Because beach pea survival is a binary event (plants either survive or do not), we used logistic regression with backward stepwise elimination to analyze the results of the experimental reintroduction. This method identified variables that best predicted beach pea survival. Backward stepwise elimination starts with all variables and omits one at a time to see what effect this has on the model to explain a particular test condition.

We evaluated six predictor variables: (1) no water/water, (2) percentage of open canopy, (3) distance to the lake, (4) foredune or blowout-type habitat, (5) plant size in June, and (6) rain in June. The logistic regression analysis identified the predictor variables that best predicted beach pea survival.

We also compared the average percentage of soil moisture among quadrats with and without supplemental watering using a nested blocked ANOVA (analysis of variation) with five blocks and two treatments (supplemental and no supplemental watering) nested within the seven sites. This analysis is used to test effects of supplemental watering.

Results

Fifty-six (16%) of the original 350 plants survived through the end of October 2008 (fig. 6). Most mortality occurred during the first few months after transplant, and the highest percentage of survival was in the quadrats that received supplemental watering. Accordingly, supplemental watering most strongly predicted high beach pea survival. Additional predictor variables associated with

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Figure 7. (Left) Project staff plant beach pea seedlings near cottonwood trees, which provide shade and help to decrease transplant shock, and behind silt fencing, which shelters the plants from sand burial. (Right) Young seedlings (three months old) were used initially, but staff soon learned that plants grown for six to eight months in the greenhouse had improved chances for survival.

increased survival were large plant size in June, increased rainfall in June, location on foredunes, and location nearer to the lake.

The average percentage of soil moisture was higher in supplemental watering quadrats, as could be expected, than in control quadrats that relied on natural precipitation throughout the growing season. All rainfall totals were within 1 standard deviation of the July–October mean for 2004–2007 (669 mm ± 110 mm [26 in ± 4 in]), meaning that the rainfall was not abnormally high or low during this period. Sand accretion within the study sites ranged from 5 to 10 cm (2–4 in) inside silt fences, and 1 to 14 cm (0–6 in) outside of the silt fences.

Population status

From the original 56 survivors of the 2008 experimental reintroduction, the population has increased tenfold. Based on the results of the reintroduction experiment, we adapted our management techniques to reflect improvements and began operations to transplant an additional 250 beach pea plants on average annually from 2009 to 2017. Our modified techniques included using larger initial transplants, planting in fall, and placing plants near nurse plants such as cottonwoods (*Populus deltoides*) (fig. 7). Nurse plants supply shade in the hot, dry conditions of the dunes and decrease transplant shock. Most of the transplants from 2009 to 2017 were to the West Site, though some went to East Site and small quantities went to other sites at Indiana Dunes National Lakeshore.

Because mature adult beach peas grown in containers have the highest survival rates, we now grow seedlings for 6–8 months before transplanting them to reintroduction sites in the fall (fig. 7). The location that originally had the highest survival rate (West Site) continues to be very productive. These plants are flowering, sending up new stems, and producing seeds. A large cohort of beach peas was planted at another foredune location (East Site) in the fall of 2015 and 2017. Many of the 2015 plantings at the East Site have survived and are producing new stems.

Discussions and lessons learned

We have a large collection of beach pea seeds collected from the nursery site and reintroduction sites, which can be used for further propagation. The best form of beach pea establishment is from seedlings grown for five to six months and then outplanted in fall. Once established at new sites these plants produce many new stems from underground rhizomes.

We did not observe many plants germinating from seeds at the parks we visited in the Great Lakes region. In the future, some of the seeds collected from the reintroduction and nursery sites can be planted along the park foredunes. If successful, this would be another method for establishing new populations.

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Figure 8. Beach peas grow on a secondary foredune at the West Site after reintroduction. This location offers protection against potential erosion from high lake levels at the primary foredune reintroduction site, which is nearer to the lakeshore.

Over the past few years the West Site has become vulnerable to more severe late fall and winter storms, and portions of these incipient foredunes have been eroded. To remediate this we have started planting beach pea farther back in secondary foredunes at West Site.

Another site in the eastern sector of the park is now showing promise, and we have supplemented existing plantings during the past three years. We have also tried plantings in later successional areas of the park, but these have not established well. Beach pea grows best in open sand areas, which have minimal plant competition, unlike conditions in late successional areas.

Survival of beach pea in some historical locations (e.g., Central Site) has been poor. Site disturbance from recreational activities, warm seasonal temperatures, and lack of sand replenishment because of structures such as jetties have likely impoverished these beach pea populations.

Transplanting of beach pea should continue at both the West Site and East Site, along with some other new foredune sites (e.g., possibly the Central Site).

With reintroduction increasingly being used as part of species recovery programs, measurable criteria for success need to be determined (Monks et al. 2012). Reintroduction success can be measured through abundance, extent, resilience, and persistence (Pavlik 1996). Several of these parameters are relevant in this reintroduction project, as follows. Beach pea at Indiana Dunes National Lakeshore is now abundant as measured by vegetative growth and fecundity, especially at the West Site. At least over the short term the population at West Site is self-sustaining, suggesting persistence, and seed dispersal may increase the species extent. Resilience, which measures genetic variation in a population, has not been measured.

Several studies could be implemented in the future to predict the viability of plantings. A population viability analysis that would include collection of demographic data could forecast the long-term survival of beach pea. Also, genetic analysis could compare the reference population to the reintroduction population to see how genetically diverse they are.

Supplemental watering most strongly predicted high beach pea survival. Additional predictor variables associated with increased survival were large plant size in June, increased rainfall in June, location on foredunes, and location nearer to the lake.

Conclusion

The growth of the beach pea population at Indiana Dunes starting in 2008 and covering a 10-year span indicates a very successful reintroduction project (fig. 8). Plants have completed their life cycle; however, we have not noted any second-generation plants germinating from seed except in one instance at the park nursery site. We have established a large inventory of seeds, with some seeds being shared with other regional land managers. Additionally we have implemented effective management techniques for propagation, established best time for planting, and developed effective follow-up care methods.

We still find it difficult to ascertain whether or not the population is self-sustaining; continued population monitoring is needed to verify population growth. We recommend continued fall planting in the existing sites (West and East), finding alternate sites for new populations, and conducting annual observation/monitoring of sites.

Because microsites for rare plants continue to be altered by various disturbances, plant reintroduction work remains an important component in the National Park Service's long-term conservation efforts for endangered plants.

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Case Studies

ONE TAM/RACHEL KESEL

The ascent to peak health: Measuring the state of a mountain's natural resources

By Michelle O'Herron

Abstract
Mt. Tam's four public agency land managers have the responsibility of caring for one of the most ecologically rich and beloved places in the San Francisco Bay Area. The mountain's natural resources provide numerous ecological, economic, and social benefits; however, these all depend on the mountain's overall health and the well-being of the constituent species that make up each of its interconnected ecosystems. A recent collaboration among Mt. Tam's land managers, the Golden Gate National Parks Conservancy, and the scientific community used the most current data and best expert judgment to understand and evaluate the mountain's ecological health. This process and its resulting products have provided an important benchmark by which managers can measure future change across jurisdictional boundaries, and have opened up new opportunities for research, collaboration, and public engagement.

Key words
ecological health assessment, ecological indicators, ecological metrics, Golden Gate National Recreation Area, Marin County Parks, Marin Municipal Water District, Mount Tamalpais State Park, Mt. Tam, One Tam, Tamalpais Lands Collaborative (TLC)

THE DISTINCTIVE SILHOUETTE OF MOUNT TAMALpais, stretching gracefully across the skyline just north of the Golden Gate Bridge, ranks among the top iconic landmarks of the San Francisco Bay Area. A mosaic of public open spaces and protected areas, Mt. Tam, as it is known to locals, extends from the shores of the Pacific Ocean, up to 2,500 feet elevation at its highest point, before sloping back down to the shores of the San Francisco Bay to the east (fig. 1).

The mountain's folded flanks and multiple peaks yield a remarkably varied topography, which, combined with a major marine upwelling zone on one side and a large estuary on the other, creates an incredible array of microclimates. A wide range of soil types within these spaces have allowed diverse plant communities to form, including several species found nowhere else in the world.

Mt. Tam is also home to threatened and endangered wildlife, including the northern spotted owl, California red-legged frog, and coho salmon and steelhead trout populations, and it provides a

MARIN MUNICIPAL WATER DISTRICT

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Figure 1. Located between the ocean and the bay and just north of the Golden Gate Bridge, Mt. Tam's blend of microclimates has given rise to tremendous ecological diversity, including (A) oak woodland habitat, (B) coho salmon, (C) northern spotted owl, and (D) manzanita.

NPS/HEATHER JENSEN

MARIN MUNICIPAL WATER DISTRICT/ANDREA WILLIAMS

welcome respite for migrant birds along the Pacific Flyway (fig. 1). As a critical link in a larger regional network of open spaces, the mountain is a natural refuge for both humans and wildlife, and its reservoirs are a source of drinking water for almost 200,000 nearby residents.

That Mt. Tam's 36,000 acres (14,569 ha) of designated open space exist right on San Francisco's doorstep is thanks to the hard work and foresight of early local conservationists; however, the mountain is a patchwork of open spaces that were protected at different times and for different purposes. As a result, its public lands are managed by four different agencies: the National Park Service, California State Parks, Marin County Parks, and the Marin Municipal Water District (fig. 2, page 56).

Even though they live in these protected areas, Mt. Tam's plants and wildlife are not immune to the threats of climate change, invasive species, habitat fragmentation, altered fire regimes, plant diseases such as sudden oak death, and noise, light, and air pollution. Interactions among these stressors (e.g., between climate change and fire frequency) further compound their effects and make managing them much more challenging. Recreational pressures are another concern for this much beloved mountain, which has more than 200 miles (322 km) of trails and receives about five million visitors per year.

While Mt. Tam's four land management agencies *had* worked together in the past to address these issues, they largely operated independently without a shared, comprehensive, strategic approach to resource management. That changed in 2014 when they joined forces with the nonprofit Golden Gate National Parks Conservancy to form the Tamalpais Lands Collaborative (TLC). The TLC focuses on priority conservation and restoration projects, coordinated education and volunteer programs, and increased volunteerism and stewardship. One Tam, the public engagement initiative of the TLC, helps galvanize community support to achieve these goals.

Building an ecological health assessment

As the TLC partners began to delve into their collective conservation and stewardship goals, it became clear that a baseline understanding of the mountain's overall ecological heath was needed to help inform their mutual priorities and to articulate a clear case for public support. It was also clear that creating such a comprehensive health assessment was going to require a collaborative, iterative, and multidisciplinary approach.

This exciting and daunting task began with an intentionally small and scientifically diverse group of staff from the TLC partner organizations, along with Point Blue Conservation Science—a key ecological monitoring and restoration partner. Limited membership in this "Health of Mt. Tam's Natural Resources Advisory Committee" (advisory committee) increased its efficiency and reduced the overall burden on agency resources. While keeping the team relatively small was important, having team members who represented a range of biological expertise also proved to be invaluable.

Recognizing that they were not the first group to attempt a large-scale ecological health assessment, the advisory committee reached out to others around the country who had conducted similar work, including the National Park Service, Chicago Wilderness Society, Conservation Lands Network, San Francisco Estuary Partnership, and the San Francisco Bay Area Wetlands Ecosystems Goals Project.

Figure 2. The TLC Area of Focus includes lands managed by four different public agencies: Marin Municipal Water District, Marin County Parks, California State Parks, and the National Park Service.

In particular, the advisory committee wanted to understand how these groups had determined their project goals, scope, scale, and process; how they defined and quantified ecological health; how and why certain health metrics were selected; and how their work had been received by various audiences. While the experiences of these groups varied widely, common themes for structuring an ecological health assessment process emerged:

1. Choose indicators that are ecologically meaningful and measurable; those that are highly valued by the public are also important to consider.

2. Engage appropriate subject-matter experts through a structured and well-organized framework to gather necessary information while maintaining the scope and scale of the project.

3. Base the initial report on existing data, as the time and expense of collecting new information can be prohibitive; data gaps will identify important areas of future study.

4. Create scientifically based, clear, meaningful, and engaging communications to share the findings.

The advisory committee ultimately decided to follow a methodology similar to that used by the National Park Service Natural Resource Condition Assessments (NRCAs). As with NRCAs, the final report was not intended to be a management document, although it did include research, monitoring, and management considerations for each ecological health indicator. Also like NRCAs, the Mt. Tam ecological health assessment relied on existing information to determine trends and conditions, confidence levels, stressors and threats, and critical data gaps; however, it also incorporated expert observation and opinion.

While starting with the right framework was critical, the last item (4) from the list of suggestions above proved to be more important than initially expected. The advisory committee worked hard early on to define the ultimate purpose and audience for this project: synthesizing and distilling the best available knowledge about Mt. Tam's resources in a way that would be useful to managers and clear and compelling to the public. Being able to return to this shared purpose was essential as the team navigated the complexities that lay ahead.

Metrics, conditions, and trends, oh my!

How to define ecological health on a mountain-wide scale?
Each of the four primary land management agencies on Mt. Tam is similarly tasked with preserving, maintaining, and maximizing biodiversity and natural processes; however, each does so under different missions, policies, and regulations. Any definition of ecological health for the entire mountain needed to encompass this range of approaches and goals, and yield a product that was useful to managers and understandable and compelling to the public.

A full and varied cache of literature exists on the many ways to define and measure ecological health, but with these goals in mind the advisory committee chose parameters that spoke to ecological function, biodiversity, species richness, resiliency, and natural processes, as follows:

1. The full complement of plants, animals, and other life-forms are present, can reproduce, and are able to find food, shelter, and water for as long as climate conditions allow them to persist on Mt. Tam.

2. Natural processes occur in a manner and frequency considered "normal" based on either historical evidence or the ability of these processes to maintain ecological functions and adapt under changing climate conditions.

3. Mt. Tam's ecosystems are resilient (able to function or recover despite disturbances, changes, or shocks).

What constitutes a "meaningful and measurable" health indicator?

If defining ecological health was challenging, figuring out how to measure it was another matter entirely. Good indicators are measurable and reveal things about other aspects of ecosystem health. The advisory committee created a comprehensive list of 37 potential ecological indicators that spoke to different aspects of ecological health and were meaningful to the partners involved in this process. These included species, taxonomic groups, communities, and ecological processes. Suspecting that many of these would prove useful, but not knowing exactly what the final assessment might include, the committee was hesitant to cut down the list early on. However, not every species, community type, or process on Mt. Tam could or should be included.

Based on the aggregated definition of ecological health above, one or more factors from the following list drove the selection of the indicators that were ultimately put forth for consideration:

- It is present in the One Tam area of focus (fig. 2).
- It is useful for measuring an important aspect of the health of the mountain (e.g., an indicator of biological integrity and biodiversity, natural disturbance regimes, or habitat quality).
- Information or expert opinion is available to draw upon to try to determine its condition or trends.
- It is a federally or state threatened, endangered, or rare species that, if lost, would have an impact on the mountain's health by the above definitions.
- It is especially iconic or charismatic, can be used to build public affinity and interest, or can be used to help gauge the health of the mountain by the above definitions.

What do we actually know about Mt. Tam's health?

The advisory committee decided to follow advice to base this health assessment on existing data and other resources. However, distinct agency priorities, missions, and budgets meant that the TLC partners had largely conducted their monitoring, inventories, research, and data management independently. Using existing data meant finding ways to reconcile information at different levels of detail, collected over different timescales using different protocols, and maintained in different formats and locations.

Good indicators are measurable and reveal things about other aspects of ecosystem health.

The advisory committee very quickly realized what a major undertaking this would be and brought on a new team member specifically to gather all available existing information and organize it into combined databases and bibliographies. This aggregated information was distilled into summary worksheets for each indicator that included important elements borrowed from the NRCA reports, including

- a preliminary assessment of the condition and trend,
- the confidence level in these assessments,
- a rationale for choosing that indicator,
- a description of the resource and its significance to the health of Mt. Tam,
- current and desired future conditions,
- proposed goals and metrics by which to measure condition and trend,
- key ecological stressors,
- existing information sources (e.g., research data, monitoring, restoration projects),
- known information gaps, and
- future planned and desired management.

Engaging the broader scientific community

Of the initial 37 proposed indicators, 24 (fig. 3, page 79) were ultimately used as the basis for a one-day workshop with approximately 40 natural resource staff scientists from all of the TLC land management agencies, the Golden Gate National Parks Conservancy, Point Blue Conservation Science, the National Park Service Inventory and Monitoring Program, and Point Reyes National Seashore. Participants broke out into facilitated, subject-specific groups to review the summary worksheets, discuss the state of agency knowledge and data sources, identify information gaps, and provide feedback on the list of proposed indicators, metrics, and condition and trend assessments.

Internal vetting was essential to helping refine and validate the proposed definitions and measures of ecological health. It also built critical understanding and investment in the process and the goals before the partners incorporated external input. Two more workshops that included 60 local academic and agency scientists relied upon the existing data and information that had been painstakingly gathered. Where data were scarce or nonexistent, participants were asked to use their best professional judgment to make a statement about goals, conditions, and trends. They also identified data gaps and areas of uncertainty, and the research or monitoring necessary to fill those gaps.

Using existing data meant finding ways to reconcile information at different levels of detail, collected over different timescales using different protocols, and maintained in different formats and locations.

As with the other stages of this process, keeping the agreed-upon end goals in mind was the key to success. Every workshop attendee understood that the final product was not meant to be a scientific research paper, but rather a scientifically based decision support and public engagement tool. They knew that they had to be willing to make a statement about conditions and trends—even if they lacked 100% certainty. And, they were clear that the focus was on defining the desired condition of each indicator and the actions needed to reach that condition.

Using the feedback from these workshops, the advisory committee set the following definitions and parameters for condition, trend, and confidence levels for each ecological health indicator.

Desired Condition: The qualities land managers and other experts consider necessary for a particular indicator to maintain its ecological function(s) and the threshold or state it should be in to be considered healthy.

Condition: The current condition of the indicator based on the aggregation of its metrics.

- Good: The condition goal is 75–100% met.
- Caution: The condition goal is 26–74% met.
- Significant Concern: The condition goal is 0–25% met.
- Unknown: Not enough information is available to determine condition.

Trend: The change in condition of the indicator based on current versus previous measure(s), independent of status (e.g., a resource may be "Declining" but may still be in "Good" condition).

- Improving: The condition is getting better.
- No Change: The condition shows no consistent trend over time.
- Declining: The condition is deteriorating or getting worse.
- Unknown: Not enough information exists to state the trend.

Confidence: The amount of certainty with which the condition and trend are assessed.

- High: Measurements are based on recent, reliable, suitably comprehensive monitoring.
- Moderate: Monitoring data lack some aspect of being recent, reliable, or comprehensive; however, measurement is also based on recent expert or scientist observation.
- Low: Monitoring is not sufficiently recent, reliable, or comprehensive; but either some supporting data exist or measurement is also based on expert or scientific opinion.

Bringing it all together

Seven individual wildlife species, three wildlife taxonomic groups, and seven plant communities were selected as indicators primarily because they had sufficient information or opinion consensus to set metrics and assess condition and trends (fig. 3, page 79). The final report clearly notes where data gaps for each indicator required the use of best professional judgment. Indicators that were deemed important, but for which there was not enough information or expert opinion, were included as needs statements for future research or monitoring (fig. 3). Seven broad, landscape-level themes were also evaluated thanks to early work to create a species-traits database that encompassed things like plant community associations, climate vulnerability, and sensitivity to ecological stressors for each indicator (fig. 3). Everyone who had participated in the scientist workshops had the opportunity to provide the technical review for the final report.

Not only has this process provided an invaluable ecological baseline for managers, but it also created excitement for the project by bringing together agency staffs and other scientists, revealing untapped synergies, and leading to new ideas for research, monitoring, and management. Completed in the fall of 2016, *Measuring the Health of a Mountain: A Report on Mount Tamalpais's Natural Resources* is being used by managers to focus their monitoring and research work, implement shared data collection, and better align their planning and budgets to support common needs.

CONTINUED ON PAGE 79

Assessing the relative vulnerability of sensitive karst habitats containing rare, threatened, and endangered species in the Chesapeake and Ohio Canal National Historical Park

By Dorothy J. Vesper, David Smaldone, and Daniel J. Feller

Abstract
We were asked to provide the Chesapeake and Ohio Canal National Historical Park with information and guidance to help park managers protect and manage karst-related rare, threatened, and endangered species on park land. To do this we developed a vulnerability risk matrix based on a variety of data collected. The purpose of the matrix was to provide the park with an interactive means of evaluating the relative vulnerability of the different sites. The data collected included (1) an inventory of karst resources in the park, (2) collection of water chemistry data, and (3) an RTE assessment. Useful outcomes included a standardized scoring system for the RTE species in the park for each site, an assessment of relative risk (vulnerability of site to negative events) and impact (a measure of the damage to RTE species if a negative event would occur), and a vulnerability matrix that identifies the sites needing management or future assessment. This matrix can be easily modified and used to assess other scenarios or to accommodate the addition of new data. Other parks and sites could reproduce this type of matrix in order to manage their resources.

Key words
caves, decision-making tool, impact assessment, karst, risk, RTE

THE CHESAPEAKE AND OHIO CANAL NATIONAL HISTORICAL Park is the most important tract of land for the preservation of rare, threatened, and endangered (RTE) subterranean macroinvertebrates in Maryland (Feller 1997). The park is home to more than 10 RTE groundwater species such as cave-dwelling amphipods and isopods that live in sensitive karst areas. The park extends 184.5 miles (297 km) along the Potomac River in Maryland and the District of Columbia, with an average width of only 290 yards (265 m). One hundred and sixty-one (161) perennial and hundreds of intermittent streams cross through the park on their way to the Potomac River. An unknown number of groundwater and surface water sources also flow from surrounding lands through the park. In a landscape undergoing rapid conversion from rural agriculture to exurban and suburban residential development, the narrow shape of this canal-based park contributes to its vulnerability to groundwater pollution originating outside the park.

Enabling legislation and National Park Service policies require that the karst features and resources be managed and preserved. The Federal Cave Resources Protection Act of 1988 (FCRPA; 43 CFR Part 37.16 USC 4301) mandates the inventory, documentation, and protection of karstic groundwaters and resources on federal lands. Such sites managed by the National Park Service need to balance public cave access with specific protections afforded under the act, including prohibiting disclosure of cave locations that protect sensitive species. The park contracted our research team to develop information and guidance for protecting and managing karst-related RTE species on park land. This article highlights the development of a vulnerability risk matrix, intended to help park staff prioritize the management needs of the park's numerous karst features.

Karst landscapes evolve because of the solubility of the underlying rocks and are characterized by caves, springs, seeps, sinking streams, and dynamic storm responses. These features are common in the park in the regions underlain by limestone, and many of these features—especially springs and cave pools—are important habitats for aquatic invertebrates (fig. 1). Unfortunately, this results in settings where surface water can be rapidly transmitted into the groundwater system, leaving the underground environment highly vulnerable to impacts such as pollution from the terrain above. Release of organic materials into these areas (livestock manure, human sewage, leaves dumped into sinkholes or caves), introduction of toxic materials (from trash dumped into sinkholes and pesticide runoff) and pathogens (leaks from septic tanks and animal waste), increased sediment in runoff, paving over of recharge areas, or pumping of groundwater for human use may adversely affect subterranean aquatic habitats and jeopardize the continued existence of these species (Dilamarter and Csallany 1986; LeGrand 1973). This may affect both water quality and quantity, which in turn can affect the sustainability of subterranean ecosystems. Except for precipitation, the quantity and quality of water that enters the park are almost completely dependent upon the land use activities adjacent to the park, which are primarily on private lands. Additionally, visitation effects, including soil disturbance from recreational cavers, are also evident at multiple caves.

Because cave and spring habitats are isolated from one another, the associated fauna has evolved into invertebrate communities

(A–B) JOHN TUDEK, (C–D) DOROTHY VESPER

Figure 1. Examples of karst features and an aquatic invertebrate found in the park: (A) a cave stream that flows intermittently, (B) a barrage tufa waterfall that forms as the result of calcite that precipitates from stream waters, (C) a spring in low-lying wooded area, and (D) a cave isopod.

with RTE species. Previous research has examined many park springs, caves, and mines for macroinvertebrates. Significant discoveries include rare species of amphipods, snails, and isopods. Biological characteristics such as low population densities, low reproductive rates, and increased longevity or the necessity of subterranean habitat for these species make karst-dependent groundwater fauna particularly vulnerable to environmental change (Culver 1982). Overall, cave- and groundwater-adapted animals represent more than 50% of the imperiled (G1 or G2 Global Conservation Status Rank as determined by NatureServe[1]) species tracked by state natural heritage programs in the United States.

The protection of recharge (source) areas for the springs, caves, and mines occurring on park land is important to the well-being of these species. We determined that the potential risks needed to be evaluated in an integrated scientific framework that involved the physical, chemical, and biological sciences. The assessment had to include an estimation of habitat and biota vulnerability from potential impacts and an evaluation of the severity of a problem if it were to occur. We developed the vulnerability risk matrix as a tool for managers to prioritize management strategies to address this difficult problem. Our approach was based on information from a number of projects, including (1) an inventory of karst resources in the park, (2) collection of water chemistry data, and (3) an RTE assessment.

1 NatureServe Explorer: An online encyclopedia of life [web application]. Version 7.0. http://explorer.natureserve.org.

Integrating project data

The karst inventory focused on 76 sites of which 59 are on park land; the sites included springs, seeps, streams, caves, and mines (Tudek and Vesper 2011). Based on our field observations, the sites ranged from permanently dry to permanently flowing water features, with numerous intermittently flowing sites. The inventory also cataloged other significant geologic, cultural, and biologic resources (e.g., barrage tufa sites, a historical signature, snow trillium) as determined by the park.

A total of 45 water samples were collected from the karst features at the park to support the karst study. The samples were analyzed for inorganic elements and compounds to help with identifying water sources. Chloride and nitrate were included as indicators of surface input from roads and agriculture. Full details were provided in the final report to the park (Vesper et al. 2016). The water chemistry for major elements was similar across the sites and did not indicate the presence of water quality issues from inorganic constituents.

The RTE assessment focused heavily on RTE macroinvertebrates found in the park's karst subterranean habitats. Investigation of these macroinvertebrates dates back to 1968 (Franz and Slifer 1971). Subsequent surveys in the 1980s discovered additional species locality records, range extensions, and new species to science (Feller 1992, 1994, 1997; Fong et al. 2007; Lewis and Bowman 2010). We incorporated biotic surveys of these macroinvertebrates into the current study to provide more complete documentation of the groundwater fauna in the study area and to update the status of historical populations. We selected priority sites to include those supporting state and globally listed rare species (S1–S2 and G1–G3), undescribed species, undetermined species, and infrequently sampled sites. We conducted surveys primarily in the spring of 2012, with additional sampling in various seasons through 2015.

We surveyed 20 sites, including 19 seeps or springs and 3 caves, for cave-obligate (cave-dependent) invertebrates with a focus on aquatic species. We sampled select sites on multiple occasions for a total of 28 sampling efforts. Sampling conditions were sometimes suboptimal (due to weather events or access issues) during dates available for fieldwork. Despite the challenges presented by sampling conditions, we made significant accomplishments. We updated records for 11 RTE species and, perhaps most significantly, discovered seven new locality records for troglobites (cave-dwelling fauna). However, we did not find several of the rarest species that had been previously documented in the park. This may be due to loss of these species or suboptimal conditions at the time of the survey.

Developing the vulnerability risk matrix model

Our approach to prioritizing karst sites for management action allowed us to focus on the most vulnerable sites rather than attempting to fully characterize recharge areas for all sites. For example, sites without water (e.g., dry caves) are unlikely to be influenced by outside-the-park contamination and, therefore, did not warrant basin mapping. Even in the case of the vulnerable wet sites, we focused on major inputs rather than identifying exact boundaries and complete recharge areas. We also provided a baseline assessment of all sites that can be used for future conservation and management decisions. The goals of the vulnerability risk matrix were to (1) prioritize sensitive karst sites based on risk level and magnitude of impacts, (2) obtain detailed information for high-risk sites to enable planning, and (3) identify needs and potential solutions for establishing protection of these habitats.

Overall matrix description and strategy
The vulnerability matrix is a means by which different locations at the park can be prioritized for management needs. There are two main components of the matrix (fig. 2):

RISK: a score that represents the potential for contamination, and assesses three key factors. The higher the risk score, the greater the potential for contamination to occur.

IMPACT: a score that represents how contamination or harmful events (e.g., vandalism) may affect or harm the RTE species. The higher the impact score, the greater the potential for damage to RTE species.

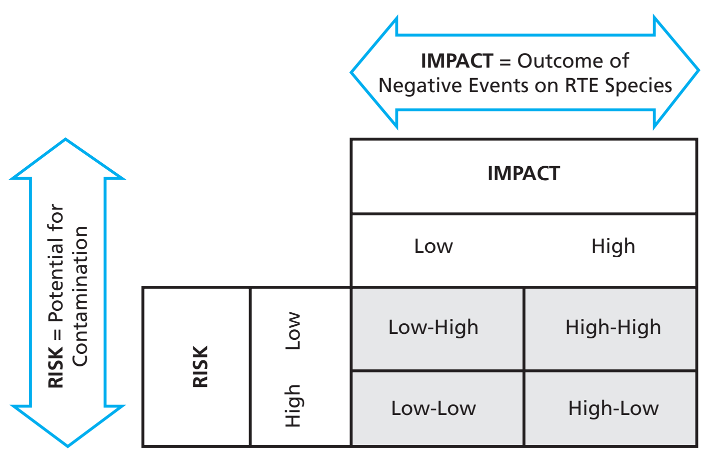

Figure 2. Vulnerability matrix that links potential risks with their impacts on the RTE species.

Water Quantity & Quality

Question	Point Range	Weight Factor
Is there water?	0–10	10
Water quality?	0–10	10
Total water risk = ∑ (points × weight factor)		

Land Use Within 1-Mile Radius

Question	Point Range	Weight Factor
Agriculture	0–10	5
Industry	0–10	5
Sewer	0–10	5
Stormwater collection	0–10	5
Total land use risk = ∑ (points × weight factor)		

Visitor-Related Issues

Question	Point Range	Weight Factor
Frequency of visitors	0–10	5
Access to visitors	0–10	5
Danger to visitors	0–10	5
Total land use risk = ∑ (points × weight factor)		

TOTAL SITE RISK =
∑ (total risks above)

Figure 3. Categories used to calculate relative RISK for each site. Point ranges and weight factors are provided as examples but can be adjusted as needed.

By comparing these two factors in matrix form, we identified four quadrants for management (fig. 2). These quadrants define the sites most important to protect (high risk–high impact), those needing the least protection (low risk–low impact), and those requiring further evaluation (mixed high and low impact).

We created this model in spreadsheet format for easy editing. It can be modified easily as priorities and project goals change.

Scoring of potential risks

We assessed the relative risk of important environmental and visitor-related categories identified by the project team (fig. 3). Given the lack of information about individual sites (e.g., area of contribution to springs, frequency of water flowing in caves), we selected topics that were general in scope.

The team decided that critical factors to include related to water quality and quantity, land use and infrastructure, and visitor-related issues. We selected final categories and adopted a strategy that would enable us to compare the different types of risks and sites. This was at times a challenge, as the following examples illustrate:

> ***Issue 1.*** Groundwater basins that contribute to springs in the park and water in park caves are extraordinarily difficult to define because very few have perennial waterflow and nearly all of the up-gradient locations are outside of the park. Additionally there are few sinkholes or possible locations where we could inject tracing dye to identify what up-gradient source areas contribute to downstream impacts. We addressed this issue by (1) defining up-gradient locations by a one-mile radius “buffer zone” surrounding each feature, but only the area on the north side of the Potomac River, and (2) including dry, intermittently flowing, and permanently flowing sources.

> ***Issue 2.*** Land use data are limited for the region. Our scoring approach was based on data that were available from the Washington County Department of Information Technology. To account for the distribution of public sewers, we relied on planning information for the county; to understand the impact of stormwater, we considered the number of permitted stormwater collection and treatment structures in each buffer zone.

For example, these data provided information on the amount of agricultural and industrial land use and the number of residents with sewer systems within the buffer zone for each karst site. We considered all agricultural and industrial land uses and the presence of septic systems (approximated by the lack of public wastewater treatment) to be potential contaminant sources that could have detrimental impacts on park karst features.

We developed an array of relative risk scores ranging from 0 to 10 points (10 being worst case) for each site risk factor (e.g., the presence of water, the lack of public wastewater treatment) based on the best available data. When data were not available and to determine relative weighting factors among the risks, we relied on professional judgment. After consultation with park specialists, we came to agreement on each risk and its associated weighting factor (table 1 and figs. 2–3). Once scores had been assigned, we multiplied each risk factor score by the corresponding weighting factor to come up with a series of risk scores for each risk category (i.e., water, land use, visitor issues). We then summed these values to get a single site risk score for each location in the park. Table 1 describes each risk category and how it was assessed. After scoring all of the sites, we divided each overall risk score by the maximum for any one site so that each score ranged between 0 and 100 and could be compared with the others. This is a process called normalization. Although the risk scores and weighting values are not absolute, the matrix approach allows for comparison of relative risks among the sites and helps identify those that may be a high priority for management action.

Scoring of potential impacts for RTE species

The impact score indicates the magnitude of a potential problem for RTE species. For example, the loss of a single habitat for a species in its "Only Known Occurrence" (OKO) has a greater impact than the loss of a single habitat for a species that is present in many locations.

To quantify impact, we considered three standard ecological descriptors for both global and state standpoints: species rank, status of species listing, and species designation as OKO. These parameters are used commonly to assess species rarity (NatureServe Explorer 2016) and are defined as follows:

- Global species rank ranges from G1 to G5, with G1 being critically imperiled and G5 being globally secure. State species ranks S1 to S5 are analogous in Maryland.
- Federal listing status defines the legal status of the species according to the US Endangered Species Act. The listing status for Maryland is similar except that the state also defines a category of "in need of conservation" that does not exist on the federal level.
- "Only Known Occurrence" is a separate category that calls special attention to these species in the evaluation process. It identifies the species that are only known to occur in one place—on either a state or global scale.

We then assigned a weighting factor to each descriptor so that their relative importance could be established. The outcome was a single impact score for each species identified at the park (fig. 4).

Once we had assigned scores to individual species, we calculated the site impact score for each location by summing the scores for

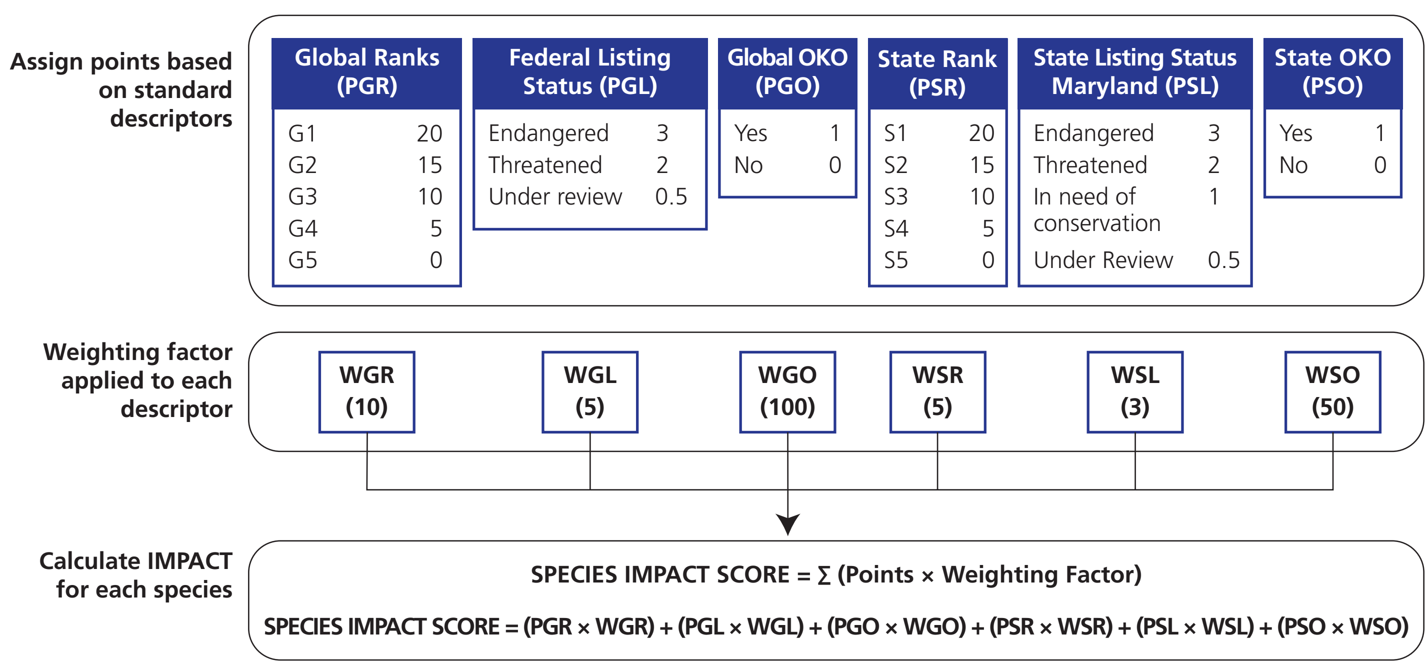

Figure 4. Approach used to generate a species impact score for each RTE species. The most vulnerable species receive the highest numeric scores. Point values and weighting factors shown can be adjusted as needed if more data become available if the categories defined for the species change (for example, more locations are found for a species previously defined as having only one known occurrence).

Table 1. Determination of scores for individual risk factors

Issue	Risk Factor	Score	Condition	Comment
Water	**Presence of Water**	0	Dry	Qualitative determination made by research team experts.
		4	Flow not seen but indications present	
		6	Pooled	
		8	Intermittent flow	
		10	Permanent flow	
	Water Quality	0	Not sampled or all chemicals below MCLs	Number of chemicals/contaminants present above EPA maximum contaminant levels (MCLs). Determined for all locations sampled for water quality during the study. Maximum contaminant levels used as the standard for comparison. Only inorganic substances were analyzed in this study, yet none were detected above their MCL.
		2	1 chemical above MCL	
		4	2 chemicals above MCLs	
		6	3 chemicals above MCLs	
		8	4 chemicals above MCLs	
		10	5 or more chemicals above MCLs	
Land Use	**Agriculture**	0	0–9% of buffer area classified as agricultural	The percentage of agricultural land cover in buffer areas. Percentages ranged from 11% to 65% for park sites.
		2	10–19%	
		4	20–29%	
		6	30–39%	
		8	40–49%	
		10	50% or more	
	Industry	0	0–9% of buffer area classified as industrial use	The percentage of land in the buffer zone mapped as industrial use. Values were less than 1% for all park sites.
		2	10–19%	
		4	20–29%	
		6	30–39%	
		8	40–49%	
		10	50% or more	
	Sewer	0	100% of residents in buffer zone on existing sewer	Washington County has not mapped its sewer system; however, regions are mapped. More than 90% of the buffer area adjacent to park sites was categorized as "no plans for future sewer systems."
		2–4	20–50% of residents on sewer; others programmed	
		6	10–20% of residents on sewer	
		8	Less than 10% of residents on sewer, but long-term plans are for sewer installation	
		10	No plans for future sewer system	
	Stormwater	0	No information	Maps for stormwater systems were not available for Washington County, but information about locations of permitted stormwater control structures was. These ranged from 0 to 6 structures within a 1 mi radius of the defined areas.
		2	More than 5 structures	
		4	4–5 structures	
		6	2–3 structures	
		8	1 structure	
		10	No structures	
Visitor-Related	**Visitor Frequency**	0	No site disturbance	Qualitative determinations were made by researchers based on field observations for all three visitor-related risk factors.
		1	Mostly undisturbed	
		2	Visitation noted but no sign of litter or vandalism	
		4	Minor damage from visitors	
		8	Litter and vandalism present	
		10	Heavily vandalized	
	Access to Visitors	0	No information	
		1	Access sealed	
		2	Locked gate	
		5	Open access but hard to reach	
		6	Open access	
		10	Open access and visible from towpath	
	Danger to Visitors	0	Appears safe, no water present	Hazards include all sites with water except for those designated as low-volume "seeps," pits, rockfall, and potential for a fall or for flooding.
		5	Minor hazards	
		10	Major hazards	

all species present at that location. These scores were the basis for the vulnerability matrix. After scoring all species, we normalized each value to the maximum number so that all scores ranged from 0 to 100.

Special designations for sites

Scoring of the RTE species did not capture all potential impacts. We identified three additional types of resources that were worth tracking:

Cultural resources—Items such as a historical signature found at one site. We designated these with a "*C".

Geologic resources—Noteworthy or pristine speleothems or unusual crystals are examples. These were designated with a "*G".

Biological resources (other than RTE)—Bat hibernacula and botanical resources (e.g., an S1 endangered plant species), for example, that are not otherwise included in the site inventory. These were designated with a "*B".

Outcomes of the potential risk assessment

Based on karst resource inventory data and additional resource information, all of the park karst sites scored from high (100) to low (46) for risk with a mean of 75 (fig. 5). These values indicate that sites range from highly vulnerable (closer to 100) to much less vulnerable (lower values). The values should be treated as relative numbers for comparison among sites.

Figure 5 illustrates the contribution of five risk factors to the highest-risk sites. Water chemistry and industrial land use categories are not shown because all park sites scored zero for these categories. For nearly all of the sites in this high-scoring group water was present along with agricultural land use in the buffer zone. The presence of sewage and stormwater was nearly uniform across all sites and therefore did not contribute significantly to the differences among them. Visitor access also scored high for the top half of this group. Overall, these results suggest that the risk at any given site is from a combination of factors, with the presence of water being critical.

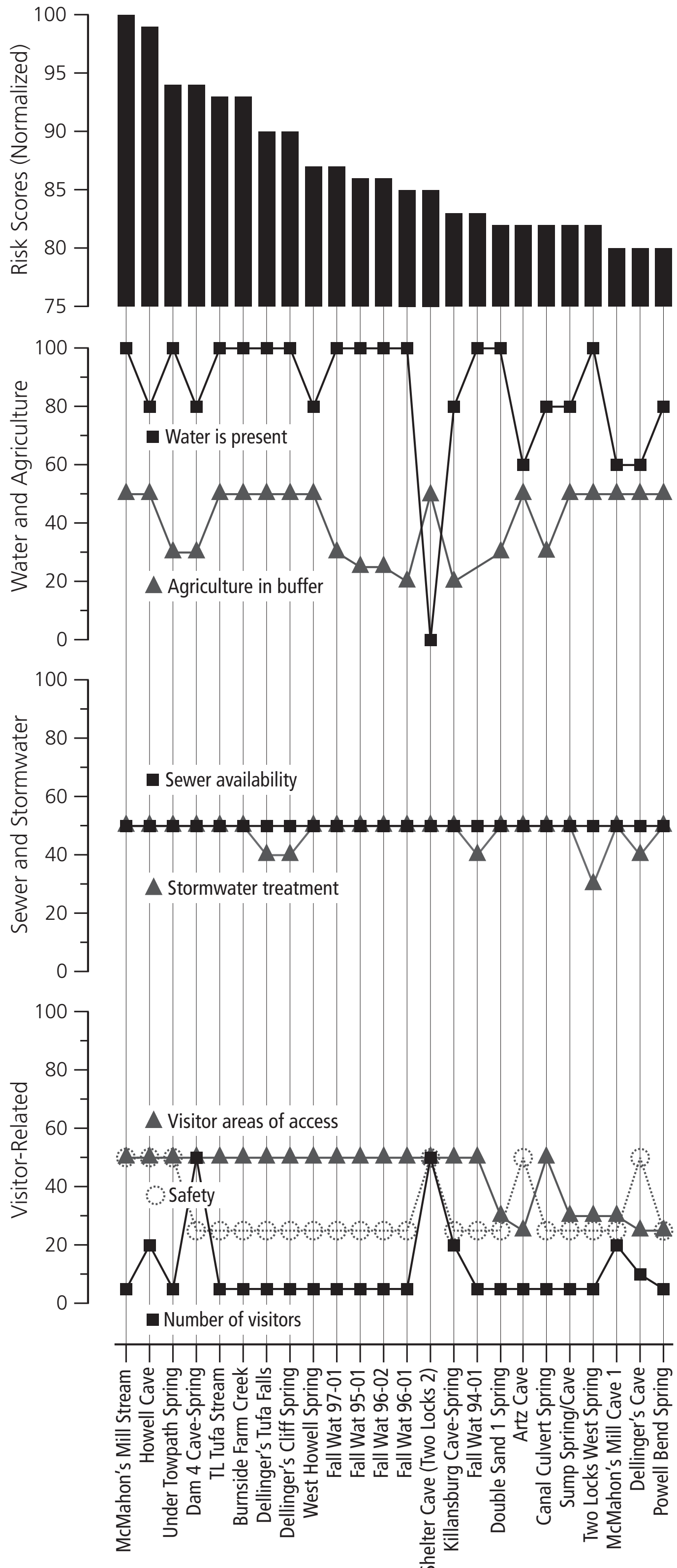

Figure 5. Contribution of factors to site risk for sites with risk scores of 80 or more. The total risk scores (top figure) and all other scores are normalized to 100 for each category, which enables the values to be compared among categories.

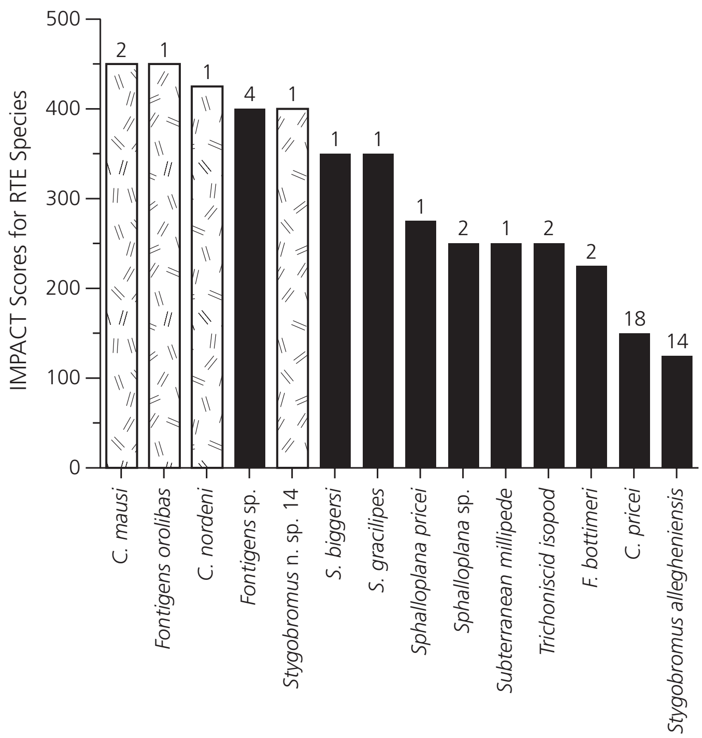

Figure 6. Impact scores for RTE species based on global and state rankings, listing status, and designation as global or state Only-Known-Occurrence (OKO). Numbers above bars indicate locations observed in the park for each RTE species. Hatch marks indicate species that are global- or state-designated OKO. *C. mausi* is listed as OKO although it was reported for two closely associated locations that are likely connected by water.

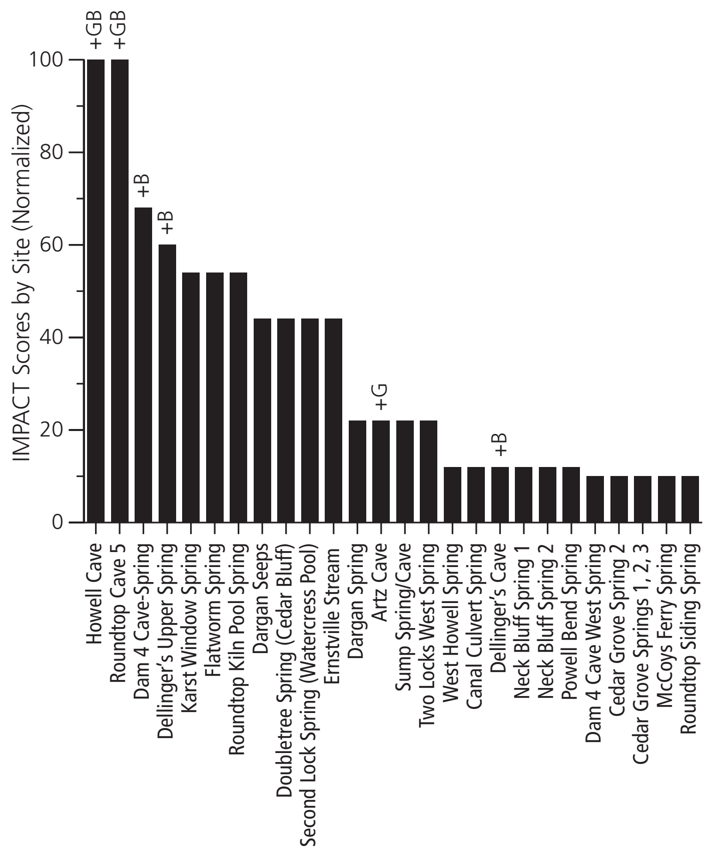

Figure 7. Impact scores for each site location were based on the number of RTE species present and state and global rankings. "+B" and "+G" indicate sites with otherwise-unaccounted-for biological or geological significance.

Outcomes of the impact assessment

Impact scores for RTE species

We based impact scores on the state and global rankings of RTE species individually and then combined them for each site. We awarded points to individual species ranging from 125 to 450, with a mean value of 338 and a median of 375 (fig. 6). Four of the five highest-ranked species are designated OKO at either the state or global level; we observed the other species as many as 18 times at the park. After calculating these initial values, we normalized the impact scores so that they could more easily be compared to the risk points.

This assessment underscores the problem of undetermined and undescribed species. For example, we scored the species known as *Stygobromus* (an amphipod) n sp. 14, *Sphalloplana* sp. (a planarian or flatworm), and the subterranean millipede (species unknown) based on their probable rarity. *Stygobromus* n. sp. 14 is likely a global OKO species found only at a single site, but at most its range is limited to three counties in Maryland. *Sphalloplana* is likely *S. pricei* (proposed endangered), *S. hoffmasteri* (endangered), or possibly an entirely new species; all possibilities are rarer than we report here. As for the cave millipede noted above, all of our knowledge about this group is from one specimen collected at the park and two others from Washington County; however, none was identified to species. Overall, this is a rare group of macroinvertebrates, and these records suggest the study area is the approximate northern limit of cave millipedes in the eastern United States.

Impact scores for site locations

Figure 7 depicts impact scores ranked from high to low for all park sites where RTE species have been observed. The initial scores range from 0 to 1,250 points, with a mean score of 186 and a median of 0. A score of 0 occurs for locations with no observed RTE species or no data. We then normalized these initial scores to aid in the comparison between risk and impact.

These results suggest that the risk at any given site is from a combination of factors, with the presence of water being critical.

Outcomes of the combined risk-impact matrix assessment

We plotted the risk and impact scores on a normalized scale to create the vulnerability matrix (fig. 8). Nearly all of the park sites have a high risk (>50%); however, sites have a wide range of these scores. Many sites had no observable RTE species and therefore have no impact score (shown as 0 on the y-axis).

Seven of the 26 locations that we evaluated fall into the high-high quadrant for risk and impact (fig. 9). Of these locations, two had scores of risk and impact greater than 75 (out of 100), identified by the gray-shaded quadrant in the figure. The park has identified these locations as management priorities. Most of the remaining sites were located in the quadrant with low impact and high risk.

Summary and limitations of the vulnerability matrix model

The vulnerability risk matrix was effective in distinguishing the relative risks and impacts among park sites. As a screening tool, this model was useful for identifying which sites are both at risk (high-risk) and need protection (high-impact). Overall, the vulnerability matrix model identified seven park sites with high-impact high-risk scores.

The inventory provided NPS managers with better knowledge of park resources, and specifically the matrix was effective at identifying sites potentially needing protection or further investigation. This type of interdisciplinary resource inventory and assessment, coupled with development of site-specific risk matrices, could be applied at other national parks or protected lands with karst resources to aid in resource management.

Though we consider it useful for assessing environmental conditions, the model is only as good as the data. It is not possible to have a study that addresses and collects data on every possible risk or type of impact (e.g., every potential contaminant in a

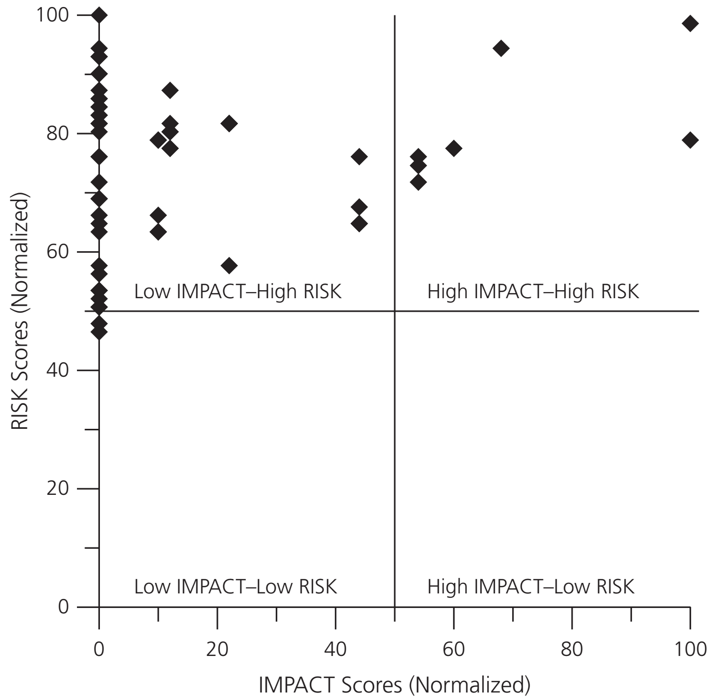

Figure 8. Vulnerability risk matrix with risk plotted against impact for park sites. Each diamond symbol on the figure is a site location.

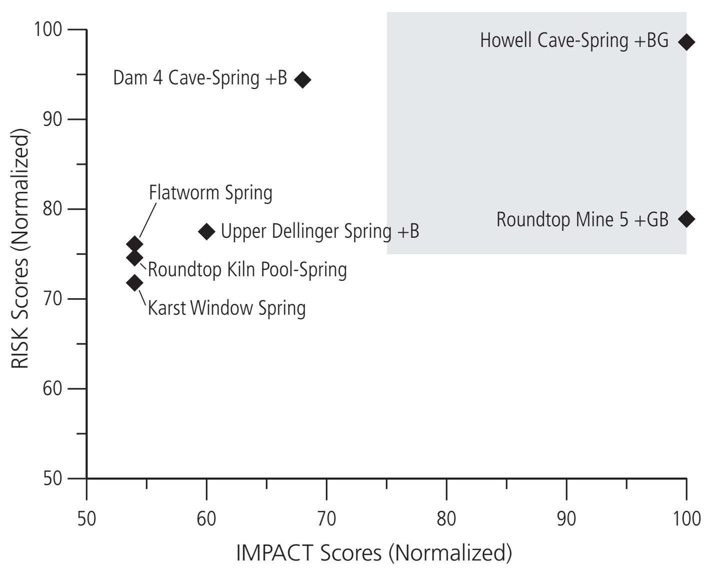

Figure 9. High-impact and high-risk quadrant of the vulnerability risk matrix with site names. "+B" and "+G" indicate sites with otherwise-unaccounted-for biological or geological significance. The shaded quadrant denotes impact and risk scores greater than 75%.

spring basin or change in species present during extreme storm conditions). The advantage of this approach is that it allows the user to integrate the data that are available and adjust the matrix when new data become available. Therefore, our assignment of points and weight values for scoring risk and impact categories should be considered preliminary and will undoubtedly be refined as our expertise with the model and availability of better information increases. For example, if RTE species become listed in the future, higher values could be given to sites where they are present to adjust for species sensitivity. We designed the model in spreadsheet format so that it can be adapted, modified, and easily learned by resource managers in various parks and protected areas. It is available on request and comes with detailed instructions.

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Literature Review

Human dimensions of winter use in Yellowstone National Park: A research gap analysis

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Abstract
This article summarizes findings from a literature review of scholarly publications and federal government documents related to winter use in Yellowstone National Park (Bricker et al. 2013). The researchers synthesized peer-reviewed periodicals and conference proceedings, government documents, and technical reports published between 1972 and 2013. We discerned and analyzed the following five research themes: (1) stakeholders and their experiences, (2) recreation impacts on park resources, (3) park management, (4) the Greater Yellowstone Area, and (5) methodology. We identified knowledge gaps that frame opportunities for further inquiry that can be useful to park managers and researchers interested in Yellowstone National Park and other protected areas with high winter use.

Key words
human dimensions, social science, winter, winter recreation, Yellowstone National Park

THE EARLIEST WRITTEN ACCOUNTS OF FORAYS INTO Yellowstone National Park during winter were made by hunters during the late 19th century. They probably entered what would become the nation's first national park on long wooden skis known as "Norwegian snowshoes" (NPS 2015c). Since then, much has changed in Yellowstone with regard to winter use. Today's winter visitors are still drawn to Yellowstone with the hope of viewing iconic wildlife, such as bison and wolves, as well as dramatic, snowy landscapes featuring contrasting, multicolored, and steaming geothermal features. However, the introduction of oversnow transportation technologies into the park, starting with snowplanes in 1949 and followed by snowcoaches and snowmobiles in the 1960s, has led to fundamental changes to park infrastructure, patterns of use, and conditions experienced by park visitors—as well as the social and economic fabric of surrounding communities (fig. 1) (Yochim 2006). As a result of real and perceived impacts of these technologies on

Figure 1 (opposite). While studies of motorized recreation and transportation have found some impacts on park wildlife and environmental quality, commercial guides were found to help mitigate impacts on wildlife while improved technologies have resulted in lowered emissions over time. Access to natural soundscapes was more important to visitors whose primary activity was human-powered transport.

park resources—in particular air quality, wildlife, and soundscape—there has been prolonged litigation and debate about what constitutes an appropriate balance among recreational access, technology, and resource protection in Yellowstone.

The conflict over winter use in the park has provided fertile ground for natural and social science researchers. Every year, the National Park Service fields requests from researchers regarding potential winter use investigations in Yellowstone. Nearly 25 years after the first winter use management plan was produced for the park, a team of researchers at the University of Utah generated a review of research regarding winter activity in Yellowstone. This review provides park managers and academic partners with a synthesis of what is known, what is not known, and opportunities for future inquiry (Bricker et al. 2013).

We started with the question, "What are the themes and gaps in the literature regarding the human dimensions of winter recreation in Yellowstone?" The term "human dimensions" in this study refers to the social attitudes, processes, and behaviors related to how Yellowstone is used by park stakeholders. The dimensions are considered at individual, institutional, community, and societal levels. Park stakeholders include (1) visitors, both domestic and foreign; (2) park staff, including park managers and frontline employees; (3) concessioner staff; and (4) constituents of the Greater Yellowstone Area.

Methods

We used a six-step, semi-inductive research synthesis method to identify themes and gaps in the literature (e.g., Cooper et al. 2009). We performed a literature search of peer-reviewed journal articles and conference proceedings, government documents, and technical reports. We delimited the study sample to materials published between 1972 and 2013, with 1972 marking the centennial of the establishment of Yellowstone National Park. This search involved several Internet databases, solicitations from Yellowstone staff to share key documents, and a reverse search through manuscript bibliographies. A detailed description of the databases and Boolean search operators used is available in Bricker et al. (2013). The references were evaluated to try to focus on those sources that were subject to a high degree of review, including refereed manuscripts and vetted government planning documents as well as additional literature reviews that included Yellowstone National Park and the surrounding area. Books, non-refereed periodicals, dissertations, and theses were excluded from the analysis. Details and justifications on the criteria used to evaluate manuscripts are also available in Bricker et al. (2013).

In order to uncover thematic categories, we first prepared an annotated bibliography of each source. Multiple readers then independently identified key topics for each one. We met twice to review and synthesize the research. Ultimately, our synthesis provided us with agreed-upon groupings of topics into five themes: (1) stakeholders and their experiences, (2) recreation impacts on park resources, (3) park management, (4) the Greater Yellowstone Area, and (5) methodology. The research synthesis did not seek to support or refute any hypotheses, build theory, or evaluate the impacts of the evidence using meta-analytic techniques (i.e., effect size). Instead, we identified subthemes based on the constructs and issues identified in seminal works (e.g., Manning 2011) and by senior researchers. We characterized these based on how often the theme had been addressed in the literature (e.g., "themes studied in two or more works" or "themes studied in one work"). Research gaps included significant themes, connections, and opportunities that were identified by either previous authors or our research team but not otherwise scientifically explored in the literature we reviewed. The list of identified gaps is not intended to be exhaustive but rather reflects the authors' review of previous literature, and seminal works of outdoor recreation authors (e.g., Manning 2011). This process provided the framework for prioritization. As such, the authors recognize and acknowledge the potential for subjective bias in developing research gaps.

Results and discussion

Citation characteristics

In total, the literature search and evaluation focused on 58 citations, including 23 peer-reviewed periodical articles, 28 government documents, five technical documents, and two conference proceedings. A full list of references is included in Bricker et al. (2013). Overall, the majority of the research-based manuscripts (i.e., not significantly related to official winter planning documents; n = 30) addressed the impacts of recreational use—especially by motorized vehicles—on natural resources, including wildlife, air quality, and the soundscape. The geographic focus of the articles ranged from specific areas within the park, to analyses of the broader context of the park in the surrounding area, and to

Figure 2. Regardless of their values, winter visitors to Yellowstone cited viewing natural scenery as the main reason for their visit. This finding was consistent for visitors on snowmobiles, who see snowmobiles as a means for viewing the park landscape, wildlife, and geothermal features rather than as a discrete recreational experience.

Figure 3. This gap analysis found many opportunities for research on stakeholders and their experiences. For example, much of the focus has been on park visitors, with only one study addressing concessioner staff and no studies examining the experiences and perceptions of gateway communities, park staff, or the nonvisiting public.

analyses of the park in the context of winter use at other national parks. Two of the manuscripts, namely Creel et al. (2002) and Cassirer et al. (1992), are "landmark" articles that have been cited more than 100 times according to Google Scholar.

While the date range of our search spanned 1972 to 2013, the earliest published document was the 1989 Department of the Interior background study used to inform Yellowstone's first winter use plan environmental assessment. Only seven documents were published between 1989 and 1999, and most of these sources focused on the impacts of snowmobiles. Forty-six documents were published between 2000 and 2009, and only six between 2010 and 2013. There was no discernable pattern to the distribution of publications based on themes addressed or document types from the year 2000 onward.

Themes and gaps

Table 1 presents the themes and gaps based on how often they were addressed in the literature. The abbreviated discussions of research themes that follow highlight key points and references. Some of the 58 references were simultaneously included under multiple themes because of overlapping findings.

Research theme 1: Stakeholders of the Yellowstone National Park experience

Seven manuscripts, all published between 2000 and 2013, explored the values, meanings, preferences, and motivations of park stakeholders (e.g., Borrie et al. 2002; Davenport and Borrie 2005; Davenport et al. 2000, 2002; Freimund et al. 2009; Mansfield et al. 2008; Tanner et al. 2008). Understanding visitor values can help park managers predict support for management decisions—values being more stable than attitudes and opinions (Yankelovich 1991). A major finding is that visitor-attributed values and motivations for visiting Yellowstone are not necessarily aligned with specific activities (e.g., snowmobiling; Borrie et al. 2002; Davenport et al. 2000). This may be because a majority of visitors to the park engage in a variety of activities during their winter visit (Davenport et al. 2000). Borrie et al. (2002), for example, found that visitors could be sorted into four clusters based on the values they attributed to Yellowstone: naturalists, human oriented, players, and park enthusiasts. Regardless of their values, winter visitors to Yellowstone cited viewing natural scenery (including wildlife and geothermal features) as the main reason for their visit (figs. 2 and 3) (Davenport et al. 2000; Tanner et al. 2008). This finding was consistent for visitors on snowmobiles, who see snowmobiles as a means for viewing the park landscape, wildlife, and geothermal features rather than as a discrete recreational experience (Davenport and Borrie 2005). This view was supported by the sole study that included concessioner staff (Freimund et al. 2009). In that study, concessioner staff perceived that visitors have

Table 1. Research themes and gaps

Categories	Themes Studied in Two or More Works	Themes Studied in One Work	Themes Not Studied (research gaps)
Stakeholders and their experiences	• Values and meanings attributed to Yellowstone by park visitors	• Link between values and support for management action • Experiences of snowmobile users • Experiences of guides and concessioners	• Comparison of different stakeholders' experiences and perceptions • Comparison of park visitors' experiences based on primary mode of transport • Place attachment in winter • Differences among seasonal experiences in Yellowstone • Values of nonvisitors • Displacement of visitors and businesses due to economic factors • Underrepresented populations and relevancy
Recreation impacts on park resources	• Air quality • Wildlife (bison and elk)	• Soundscape • Water • Wildlife (excluding bison and elk)	• Cultural resources • Night sky and light pollution • Vegetation
Park management	• Physical carrying capacity • Air quality at park entrances	• Standards and indicators of environmental quality • Nonmotorized recreation	• Social carrying capacity • User conflict between recreation types • Recreation diversity • Public consultation process evaluation • Demand/impact studies of park facilities and infrastructure
Greater Yellowstone Area	• Economic impacts of Yellowstone on Greater Yellowstone Area	• Economic impacts of motorized recreation	• Differences in snowmobiling experiences: Yellowstone vs. nearby national forest lands • Attitudes of area residents toward park management • Economic impacts of wildlife tourism • Economic value of ecosystem services • Dynamics of amenity migration (residents who move to a location because of proximity to recreational opportunities)
Methodology	• Quantitative research approaches	• Qualitative research approaches	• Qualitative approaches (e.g., ethnographies) • Social-spatial mapping • Long-term studies • Follow-up studies • Systematic reviews

changed from those using the park to experience snowmobiling to those who use snowmobiling to experience the park. The same research also found that concessioner staff believed that visitors appreciated the guided oversnow vehicle experience because of the transfer of knowledge that occurred through the interpretive services. These findings suggest the need to focus management planning and policies on the overall park experience rather than discrete activities.

This gap analysis found many opportunities for research on stakeholders and their experiences. For example, much of the focus has been on park visitors, with only one study addressing concessioner staff and no studies examining the experiences and perceptions of gateway communities, park staff, or the nonvisiting public. Research questions that target the values, experiences, and perspectives of these stakeholders, especially with respect to their influence on park management strategies, would help fill this gap. For example, what are the values attributed to the park by nonvisitor stakeholders? What is the extent of place attachment among winter guides or park staff? And how has use by local residents changed since the new commercial guide and best available technology (BAT) for snowmobiles requirements were introduced in 2004 and finalized in 2013? Additionally, a number of avenues remain to be investigated regarding park visitors. Comparative studies of the summer and winter seasonal experiences, of visitor experiences based on modes of transport, and of value orientations between visitors and nonvisitors (including park staff, concessioner staff, and citizens of the local community as well as the public at large who does not visit the park) could provide useful insights for park managers. Another possibility would be to explore the dynamics surrounding traditionally underrepresented groups in national parks, such as visible minorities (Taylor et al. 2011), as well as displaced concessioners during the winter season.

Research theme 2: Recreation impacts on park resources

Twenty-three manuscripts focused on the impacts of recreation and transportation, especially of motorized vehicles, on park wildlife and environmental quality (air quality, water quality, and soundscape). A complete list of those references is available in Bricker et al. (2013). As already reported, "wildlife is a major component of the Yellowstone experience" during winter (Caslick 1997, p. A-5). Visitors expect to see wildlife and value the park's mandate to protect it (Tanner et al. 2008). The parks in the Greater Yellowstone Area (Yellowstone and Grand Teton National Parks and John D. Rockefeller, Jr., Memorial Parkway; also see theme 4) protect the largest and most diverse number of animal species in the contiguous 48 states, including a federally listed threatened, charismatic species—the Canada lynx (*Lynx canadensis*)—as well as the recently delisted grizzly bear (*Ursus arctos horribilis*), gray wolf (*Canis lupus*), and bald eagle (*Haliaeetus leucocephalus*) (RTI International 2007). With the restoration of the gray wolf starting in 1995, the park is once again home to the same assemblage of large mammals present during precolonial times (NPCA 2006).

Winter visitors interact with wildlife while pursuing various outdoor activities, and the literature reports a variety of impacts on wildlife within the park. These include habituation of wildlife to humans, habitat disturbance, disrupted foraging behavior, interference with breeding behavior, and physiological stress responses during harsh winter conditions (Olliff et al. 1999). Wildlife responses depended on a number of factors, including (1) whether visitors stop, dismount, and approach the animal; (2) human interaction time; (3) number of vehicles; (4) proximity of animals to the road; and (5) size of animal group (Borkowski et al. 2006). Studies of wildlife (in particular elk, bison, and trumpeter swans) responses to oversnow vehicles (OSVs) found some impacts; however, 72% of the wildlife showed no visible response, with less than 1% fleeing from the area in response to vehicles (McClure 2009). Commercial guides were found to help mitigate impacts through a number of interventions (e.g., stopping at greater distances from wildlife, keeping people close to vehicles; McClure 2009). Regarding air quality, one of the main findings was that large reductions in emissions were achieved over time with changes to the models, engine sizes, engine cooling types, and technologies used in the park's OSV fleets (Bishop et al. 2009). Regarding water quality, the levels of volatile organic compounds present in Yellowstone's surface water runoff have been found to be within acceptable limits as established by the US Environmental Protection Agency (Arnold and Koel 2006). Regarding soundscapes, Freimund et al. (2009) found that visitors to the Old Faithful area expect to hear natural soundscapes, but those whose primary activity was human-powered transport (i.e., skiing or snowshoeing) thought that natural sounds were more important than the other groups.

The gap analysis found many opportunities for additional research on winter use impacts on park resources. Nonmotorized recreation has not been fully assessed. Concerning wildlife, little research has examined the impacts of winter use on grizzlies, wolves, bighorn sheep, mountain goats, and mid-sized carnivores such as bobcats, lynxes, martens, red foxes, fishers, and weasels that may be susceptible to behavioral and physical impacts. Studies of the impacts on vegetation, dark skies (light pollution), and cultural resources were also not found in our literature review, and more research is needed to measure noise impacts over long distances in remote environments (e.g., Menge et al. 2002). In terms of anticipating emerging technologies that may cause additional resource disruption, a 2014 NPS interim policy prohibits the use of recreational unmanned aircraft and drones in national

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park units (NPS 2017). Arnold and Koel (2006) call for research on potential impacts from polycyclic aromatic hydrocarbons from engine emissions, which are known to be harmful to human and animal health and to be more persistent in the environment than previously studied volatile organic compounds. They also call for research on the impacts of vehicle fluids leaked on snow roads, noting that all of Yellowstone's waterways are classified as Class 1 Outstanding Natural Resource Waters, a designation that ensures a high level of protection and is enforceable under provisions of the Clean Water Act (Arnold and Koel 2006).

Research theme 3: Park management

Sixteen manuscripts focused specifically on issues related to park policy and planning documents. Since the publication of Yellowstone's first winter use plan in 1990, the National Park Service has completed a number of management plans that consider seasonal changes in resource access and management (e.g., Dustin and Schneider 2004; Yochim 2006; NPS 2015b). Many of these involved collection and synthesis of data related to various structured decision-making frameworks, including Limits of Acceptable Change models (NPS 2008, 2011; Sacklin et al. 2000) and Recreation Opportunity Spectrum tools (NPS 2007, 2008, 2011). Several studies on theme 2 were also specifically developed in the context of park policy decisions related to OSV carrying capacity, air quality, and the impacts of snow road grooming on wildlife.

Because the sources in this category were policy driven, there are a number of gaps and opportunities for additional related research. For example, while several studies referred to physical carrying capacity in the context of OSVs (e.g., Arnold and Koel 2006; Borkowski et al. 2006), there were no studies of social carrying capacity, or studies on conflicts between types of recreationists or on recreation diversity. The Recreation Opportunity Spectrum model has been used in winter planning (e.g., NPS 2008, 2011) but it has not been evaluated for its efficacy in this context. Public consultation has likewise been a planning component since the first park winter plan, but no evaluations of the efficacy of the National Environmental Policy Act methods and techniques in Yellowstone were located in this literature search.

Last, during the winter season an array of infrastructure, facilities, and services are maintained in Yellowstone, including privately run hotels, transportation, and guiding services in the park. With the exceptions of the impacts of groomed roads on wildlife (e.g. Bjornlie and Garrott 2001; Bruggeman et al. 2006) and impacts of idling OSVs on air quality (e.g., Bishop et al. 2009), park facilities and infrastructure received scant attention in the literature.

Research theme 4: Greater Yellowstone Area

Eight manuscripts focused on the relationship between Yellowstone National Park and its broader context—both in ecological and human terms (Jobes 1991; NPCA 2006; NPS 2004, 2007; Olliff et al. 1999; RTI International 2004, 2007; Yochim 2006). The Greater Yellowstone Area includes 20 counties in Idaho, Montana, and Wyoming that are part of the 34,375-square-mile (89,031 square km) Greater Yellowstone Ecosystem, one of the last remaining large, nearly intact temperate-zone ecosystems on Earth (NPS 2015a). The literature confirms that tourism comes with its own social and environmental challenges, among them the fragmentation of habitat in the Greater Yellowstone Ecosystem (NPCA 2006; Olliff et al. 1999). In human terms, the most prevalent research question addressed on this theme was the economic impact of Yellowstone National Park on surrounding communities (NPCA 2006; NPS 2004, 2007; RTI International 2004, 2007). One of the key findings is that Yellowstone National Park plays an important social and economic role both regionally and nationally (Jobes 1991; NPCA 2006). Another finding is that planning in Yellowstone is politically charged, with substantial investments made by national motorized recreation interests (Yochim 2006).

A number of gaps remain concerning the interactions between the park and its context. As noted under theme 1, research is needed regarding the values, perspectives, and experiences of surrounding residents, particularly in relation to park use, park management, and place attachment. The question of how park policies, including rules around concessioner permitting, influence the social and economic structures of gateway communities should also be explored. Similarly, the dynamics of amenity

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migration—when people move to an area for reasons other than economics, such as physical or cultural amenities and the impacts of seasonal tourism-related work—are also a topic yet to be examined. And finally, the economic impacts of wildlife tourism, the economic value of ecosystem services provided by Yellowstone, and differences in snowmobiling experiences inside and outside the park are also viable avenues for research.

Research theme 5: Methodology

The research synthesis found a lack of diversity in research approaches. Commonly used quantitative research approaches included (1) measurements of air quality, water quality, exhaust emissions, and sound levels of OSVs; (2) economic impact analyses of proposed management actions; (3) observer surveys recording human-wildlife interactions and wildlife responses to human stimuli; (4) OSV counts; and (5) visitor surveys of preferences, values, personal characteristics, and recreation activities (mail-in and on-site). Less commonly used approaches included radiotelemetry, benefit-cost analyses of Yellowstone-related tourism in the Greater Yellowstone Area, and measurements of stress hormone levels of wildlife in response to interactions with OSVs.

These results indicate several methodological gaps. When appropriate to the research question, future research might benefit from qualitative approaches, including case studies, interviews, focus groups, and ethnographies. Social-spatial mapping approaches could be used as well, including GPS visitor tracking (Beeco et al. 2014) and public participatory GIS, such as social-values mapping (Van Riper et al. 2012). The research synthesis did not uncover any evaluative, longitudinal, or follow-up studies; given the changing regulatory context, such studies would be useful in tracking trends and responses to new regulations. Future review-oriented research also could consider incorporating books and non-peer-reviewed material, such as dissertations and theses, into research syntheses.

Conclusions

This study provides a synthesis of the catalog of research on the human dimensions of winter use in Yellowstone National Park. Systematic reviews of research such as this allow park managers, researchers, and academics to assess the state of knowledge about their park on an ongoing basis. The gaps in knowledge and opportunities for further research can be useful to managers and researchers at Yellowstone and other parks with similar winter use profiles.

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INDICATORS

Plant Communities
- Coast redwood (*Sequoia sempervirens*) forests
- Sargent cypress (*Hesperocyparis sargentii*)
- Open-canopy oak woodlands
- Shrublands: Coastal scrub and chaparral (including serpentine chaparral)
- Maritime chaparral
- Grasslands
- Serpentine barren community endemics

Wildlife Species and Groups
- California red-legged frog (*Rana draytonii*)
- Foothill yellow-legged frog (*Rana boylii*)
- Western Pond Turtle (*Actinemys marmorata*)
- Northern spotted owl (*Strix occidentalis caurina*)
- Osprey (*Pandion haliaetus*)
- American badger (*Taxidea taxus*)
- North American river otter (*Lontra canadensis*)
- Anadromous fish
- Birds
- Mammals

Broad Ecological Themes
- Overall Mt. Tam biodiversity condition and trend
- Climate-vulnerable plant communities
- Climate-vulnerable bird communities
- Shrubland ecosystems
- Grassland ecosystems
- Open-canopy oak woodland ecosystems
- Coast redwood forest ecosystems

INFORMATION GAPS

Gaps in Data
- Seeps, springs, and wet meadows
- Riparian woodlands and forests
- Hardwood forests and woodlands
- Douglas-fir forests
- Lichens as an indicator of health (climate and air quality)
- Soils
- Hydrologic functions
- Insects
- California giant salamanders (*Dicamptodon ensatus*)
- Small mammals, especially bats

Figure 3. Ecological health indicators selected for the final report that were measurable, revealed something about the broader ecological health of the mountain, and had sufficient existing data or expert opinion. Information gaps identify important areas for future inquiry.

The report and its related communication materials have also achieved the initial goal of bringing the best available information together in a clear and publicly meaningful way. A summary video, brochure, and interactive web dashboard distill the report's findings in accessible and compelling formats. Additionally, hundreds of members of the public, along with the local scientific and conservation communities, have attended two annual symposia on the outcomes of the project.

These efforts have been invaluable for engaging stakeholder groups and other members of the public, and helping to illuminate how Mt. Tam's multiple land managers use science to protect and restore its important and unique resources. They have also created pathways for collaboration and understanding as managers plan for the mountain's future.

About the author

Michelle O'Herron *is an independent science communication and landscape partnerships consultant (www.oherrron.co). For more information about this project please visit the One Tam Peak Health website at http://www.onetam.org/peak-health, or contact Sharon Farrell at sfarrell@parksconservancy.org or Bill Merkle at bill_merkle@nps.gov.*

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