# YELLOWSTONE SCIENCE

## VITAL SIGNS

Monitoring Yellowstone's Ecosystem Health

# A Healthy Look at Monitoring

Yellowstone National Park is a 2.2 million-acre sprawling oasis containing some of the most spectacular scenery on earth. Unsurprisingly, the United Nations has identified Yellowstone as a World Heritage Site and Biosphere Reserve, highlighting its outstanding universal value and significance to the world. Formal protection of Yellowstone in 1872 was a conservation milestone and represents an exemplar of protected area conservation that today is emulated by nearly 100 other nations. We should never miss an opportunity to celebrate those early park visionaries or lose sight of the value of this enduring natural and cultural resource to societies past, present, and future. While early proponents helped establish management boundaries that define and protect the diverse habitats that together form Yellowstone, these boundaries and the added protections of neighboring public lands that make up the Greater Yellowstone Ecosystem (GYE) will not shelter the park from outside forces that are changing the health of its ecosystems (e.g., climate change, non-native species, wildlife disease, and land-use change on areas bordering the park).

Temperatures on earth are rising, droughts and extreme weather events are becoming increasingly common, and biodiversity declines are widespread. Global declines of insects, amphibians, birds, and mammals are extraordinary—losses of vertebrate species are 100 to 1,000 times greater than centuries past. Yellowstone, despite its massive size, global importance, and careful protection, is not isolated from the influences of these ecological drivers. The impacts of these drivers on habitats and species assemblages are unclear and are likely to complicate management of this iconic park. However, a monitoring program analogous to that used in human health offers a meaningful strategy for assessing and tracking the health of Yellowstone's ecosystems. Such a program would use reliable and standardized measurements of "vital signs" to establish ecological reference points or baselines, assess whether park ecosystems are operating within natural limits, or identify thresholds that should not be crossed.

Central to understanding Yellowstone's health is high quality ecological information gathered as part of a comprehensive vital signs monitoring program. Absence of such information constrains park managers from responding to changes in habitats and their biological communities or understanding the effectiveness of ongoing management actions (e.g., non-native fish removal) and surveillance (e.g., for wildlife disease). Fortunately, the National Park Service has been championing the monitoring of select vital signs in Yellowstone and neighboring public lands for more than a decade. In this issue of *Yellowstone Science* several themes emerge: 1) the need for increasing the number of vital signs monitored, 2) the importance of expanding monitoring programs across the GYE, and 3) the value of regular communication of trends in vital signs to decision makers and the public.

The early proponents of wildland conservation exercised extraordinary vision when they proposed the establishment of America's first national park. In this era of rapid environmental change, declining trends in population sizes, and increased species extinction rates, we must also be forward-looking in our anticipation of future change and formalize a monitoring program that carefully tracks and regularly assesses the most vital indicators of ecosystem health. The environmental data gathered now and into the future will support clear-eyed assessments of the health of Yellowstone and the GYE and serve as the basis for informed decision-making for generations to come.

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**Greater Yellowstone Inventory and Monitoring Network**

**National Park Service**

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## FEATURES

## DEPARTMENTS

**On the cover:** A vocalizing boreal chorus frog and Blacktail Ponds. Blacktail Ponds have been included in annual amphibian vital sign surveys since 2006. These deep, permanent ponds will become increasingly important habitat for chorus frogs and other amphibians in a warmer and drier future. These ponds also contain introduced fish which can prevent chorus frogs from using otherwise viable wetland habitats. Long-term vital signs monitoring will continue to provide managers with information on the complex, interactive effects of multiple stressors on Yellowstone's amphibians. (NPS Photos - N. Herbert)

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# Vital Sign Monitoring is Good Medicine for Parks

### *by Andrew Ray, David Thoma, Kristin Legg, Robert Diehl, Adam Sepulveda, Mike Tercek, & Robert Al-Chokhachy*

Nearly 70 years ago, a young ranger naturalist working in Yellowstone National Park (YNP), Frederick B. Turner, became fascinated with the abundance of frogs next to his cabin at "Soldier Creek" (known as Lodge Creek today). This interest blossomed into Turner's PhD research and his publication in 1960 about the local population of Columbia spotted frogs (shown to the right) became a classic for herpetologists. Unfortunately the frog population Turner studied had a less positive future in store. Research by Idaho State University biologists in the 1990s revealed that the population had dwindled by 80%. Now, most of Turner's study area is bereft of spotted frogs, and the remnant population near Yellowstone Lake is affected by a steep decline in reproduction and frequent disease outbreaks. Meanwhile, amphibian population declines documented worldwide, including in national parks of the western U.S., have become common. In YNP and neighboring Grand Teton National Park, we face the important questions of whether widespread amphibian declines are occurring here and if so, what they portend. Can amphibians inform us about the health and changing conditions of wetlands in YNP? What are the implications of diminishing wetlands for other water-dependent species? And, more broadly, can amphibian and other living organisms serve as reliable indicators or vital signs for park health? In this issue of *Yellowstone Science*, we discuss how ecosystem science is taking cues from the medical field by relying on vital sign monitoring programs to assess ecosystem health.

Medicine is almost universally recognized as the scientific practice of identifying, preventing, and curing disease. The word "medicine" comes from *med*, meaning thought or meditation in Latin and give attention to or think about in Greek (Charen 1951). Those who practice medicine should, therefore, have sound judgement and the ability to see, think about, and treat patients as a whole while understanding there is natural variation in vital signs among individuals and, to some extent, individualized responses to both disease and treatment. Practitioners must also have humility, a willingness to acknowledge uncertainties, and the capacity to consider and evaluate all of the available evidence of illness in the context of family history and environmental influences.

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Ecosystems, like the human body, are complex arrangements of distinct components working together to function properly and respond to outside stimuli. In ecosystem medicine, disease can be considered more broadly as a departure from the normal range of variation and a process which transforms ecosystems to a state where associated health and vitality are diminished (Rapport et al. 1979). As with medicine, a misdiagnosis is possible, but science reduces uncertainty by helping understand how interacting components of complex systems work together. Today, vital human and ecosystem characteristics are monitored using select biological, chemical, and physical indicators. Because of the utility of indicators for monitoring human and ecosystem health, the term "vital signs" has been embraced by both medical and ecological disciplines.

## Vital Signs

In medicine, vital signs such as blood pressure, body temperature, and pulse rate are simple routine measurements used to quickly assess health. Although the normal range of human vital signs varies across age groups and ethnicities, when tracked over time vital sign measurements serve as individual baselines or reference points, contribute to diagnoses, and support decisions concerning the response of patients to medical treatments. Slight abnormalities in vital sign measurements (e.g., elevated body temperature) are usually not critical but may warrant additional screening, whereas extremely abnormal vital signs may indicate a life-threatening condition requiring an immediate medical response.

In ecology, vital signs such as snowpack depth, air temperature, and water flows and chemistry serve as similarly simple and routine measures that assess ecosystem health. Because of their value to decision makers, vital signs and broader biological monitoring ("Surrogate Species: Piecing Together the Whole Picture," this issue) efforts are being widely used to understand and measure the health of plant and animal populations, ecosystems, parks, and even the Earth itself. The overarching goal of vital signs monitoring is to characterize a "safe operating space" or natural or historical range of variation from which future departure can be assessed and, where possible, changes can be mitigated (Röckstrom et al. 2009, Scheffer et al. 2015). The most practical vital sign indicators support management decisions and policies that promote ecological health and track changes in resources that people value (see inset - Supporting Management Decisions which Promote Ecological Health). For example, the U.S. Geologic Survey and U.S. Bureau of Reclamation have monitored river flows and reservoir levels across the Greater Yellowstone Ecosystem (GYE) for decades. Monitoring data have proven valuable for flood prediction and for the allocation and delivery of irrigation water to downstream users but also for informing management strategies that protect native trout and other cold water species. Vital signs monitoring can also contribute to a deeper understanding of past management actions (see inset - Documenting Responses to Past Management Actions) and uncover associations that support forecasting of future conditions (see inset - Forecasting Future Change). As an example, snowpack declines over the last century have been well documented (Pederson et al. 2011). Forecasts for YNP's snowpacks indicate earlier melting and the continuation of snowmelt declines. While declines are expected to be widespread, regional variation will be considerable (Tercek and Rodman 2016); this understanding will provide decision makers options for minimizing impacts to winter recreation. Finally, vital signs monitoring can serve to document current conditions providing baselines from which future departure can be assessed. For example, scientists in YNP and across the National Park Service (NPS) are actively working to characterize the natural soundscapes of parks ("What We're Listening to: How Sound Inventories Can Contribute to Understanding Change," this issue). Today, acoustic monitoring techniques are helping park staff understand and fully characterize biodiversity (Buxton et al. 2018), develop noise mitigation programs, and document contemporary conditions (Lynch et al. 2011) from which future change can be evaluated. As parks continue to witness expansion of infrastructure and urbanization on neighboring lands and brace for a future with even more visitors, these baseline datasets and others described in this issue will become increasingly valuable.

## Supporting Management Decisions Which Promote Ecological Health

Vital signs monitoring is a crucial part of ecosystem science and monitoring data are often useful for multiple purposes. Overall monitoring costs are relatively minor relative to the value of the resources protected and policies informed (Lovett et al. 2007). Across the GYE, the U.S. Geological Survey and NPS monitor river flows and water quality, including water temperatures. Collectively these vital signs represent the primary factors influencing which fish (e.g., Yellowstone cutthroat trout) and invertebrates are present within a waterbody. There is overwhelming evidence showing that river flows and water temperatures are affected by a changing climate. Specifically, warmer air temperatures and smaller snowpacks produce lower summer flows and higher water temperatures in YNP's and regional rivers (Al-Chokhachy et al. 2017). Documented changes in river conditions have contributed to temporary fishing closures on some of YNP's rivers, a measure designed to protect stressed fish during the hottest days of the fishing season (NPS 2017). Angling restrictions in regional rivers (e.g., Montana; MT Rule 12.5.501) due to drought are triggered when summer flows fall below the 5th percentile of daily mean flows (i.e., lower than the 5 lowest flow years out of the 100-year record) for that calendar day. Although closures restrict angling opportunities on some rivers in some years, decisions to temporarily close a stretch of river is a simple, actionable measure managers use to safeguard fish from the added stress of angling during periods when low flow thresholds are exceeded. For anglers, there is a growing understanding and widespread support for responsible management practices (e.g., temporary, temperature or disease-induced closures) implemented to protect public resources and ensure the long-term viability of fisheries (French 2016).

## Documenting Responses to Past Management Actions

Long-term monitoring data can be used to effectively evaluate vital sign responses to past management actions, experimental manipulations, or interventions (Lindenmayer and Linkens 2010). Water quality monitoring in YNP's Soda Butte Creek offers an example of how long-term monitoring data was used to evaluate water quality improvements associated with the reclamation of an abandoned mill and tailings site located near the town of Cooke City, Montana. The goals of the McLaren Reclamation Project were to remove an unstable tailings impoundment, relocate contaminated floodplain sediments, improve water quality, and restore the ecological health of Soda Butte Creek (Henderson et al. 2018). Following completion of reclamation activities in 2014, vital signs monitoring data showed that reclamation activities effectively eliminated the principal source of iron and other metals in Soda Butte Creek and protected downstream waters in YNP from the legacy left by abandoned mines. Importantly, long-term water quality monitoring data from Soda Butte Creek also supported a determination by the Montana Department of Environmental Quality (MTDEQ) Water Quality Bureau that metal conditions in Soda Butte Creek were sufficiently restored to warrant removing Soda Butte Creek from Montana's 303(d) Impaired Waters List. For MTDEQ, the NPS, and other project partners, this marks a first in Montana for delisting an impaired water body following the successful implementation of abandoned mine cleanup (Henderson et al. 2018). For local residents, this restoration of ecological health was celebrated by the return of recreational and angling opportunities lost through several decades of mine-related impairments. Coordinated vital signs monitoring provided information necessary to understand the magnitude of water quality improvements in Soda Butte Creek and characterize elements of ecological recovery associated with this notable management action.

## Long-term Monitoring at Ecologically Relevant Scales

Long-term vital signs monitoring when conducted at ecologically relevant temporal and spatial scales can help shed light on shifts in the timing (i.e., phenology) of biological processes; changes in composition of biological communities; variations in the abundance, spatial coverage, and duration of annual snowpacks; and fluctuations in a multitude of other important ecological processes. Well-crafted vital signs monitoring programs can also help attribute changes in vital signs or vital sign responses to multiple, potentially interacting changes to climate drivers (e.g., snow, air temperatures) and the addition of other modern stressors (e.g., establishment of invasive species, increased recreational use, and novel diseases). These changes can occur simultaneously or be greatly exacerbated through a single pulse such as the introduction of invasive species ("Yellowstone Convenes Science Information Sharing Panel on Aquatic Invasive Species," this issue). Although there are many nuances associated with the discussion of monitoring and scale, long-term ecological monitoring at ecosystem or regional levels is increasingly needed for assessing the health and carefully managing large protected areas for the benefit of future generations (Hansen and Phillips 2018, Watson et al. 2018)

In particular, broadscale monitoring at ecosystem or regional scales has revealed unexpected findings about the spatial variation of past change and offers discoveries at scales that cannot be manipulated in traditional lab or field experiments (Sagarin and Puchard 2010). As examples, consider how our current understanding of antelope, mule deer, elk, and grizzly bears has been shaped by monitoring animals throughout annual migrations and documenting long distance movement patterns across the GYE. The early studies of grizzly bears documented regular movements outside of park boundaries and helped launch conversations about the need for coordinated monitoring and management of the species at a regional scale (figure 1). Since 1973, federal, state, and tribal scientists have been working collaboratively as the Interagency Grizzly Bear Study Team to monitor grizzly bear dynamics and share information on the distribution and habits of grizzly bears across the region (van Manen et al. 2017). Like grizzly bears, many species move freely across portions of the GYE and similarly benefit from coordinated, long-term monitoring efforts. Monitoring migratory pronghorn, mule deer, and elk (Roth 2018) has contributed to the protection of important summer and winter range as well as the identification of key migratory routes. Similarly, regional monitoring has led to the identification and protection of regional strongholds for native grayling and cutthroat trout (Gresswell 2011), and the long-term conservation of one of the GYE's most iconic species, whitebark pine, will continue to benefit from coordinated monitoring and boundary-spanning conservation strategies ("An Uncertain Future: the Persistence of Whitebark Pine in the Greater Yellowstone Ecosystem," this issue).

Today, ecological vital signs monitoring programs are working at park, regional, and national spatial scales (Rodhouse et al. 2016) to employ reliable and standardized measurements to assess whether physical or biological indicators are within a natural range of current or historic variation (Röckstrom et al. 2009) or whether they are nearing boundaries that should not be crossed (Radeloff et al. 2015). In YNP the detection of non-native lake trout in the relatively simple Yellowstone Lake food web represented the crossing of an ecological boundary that warranted an immediate and intense response and one that prevented an ecosystem from "tipping" into an undesirable and unrecoverable condition.

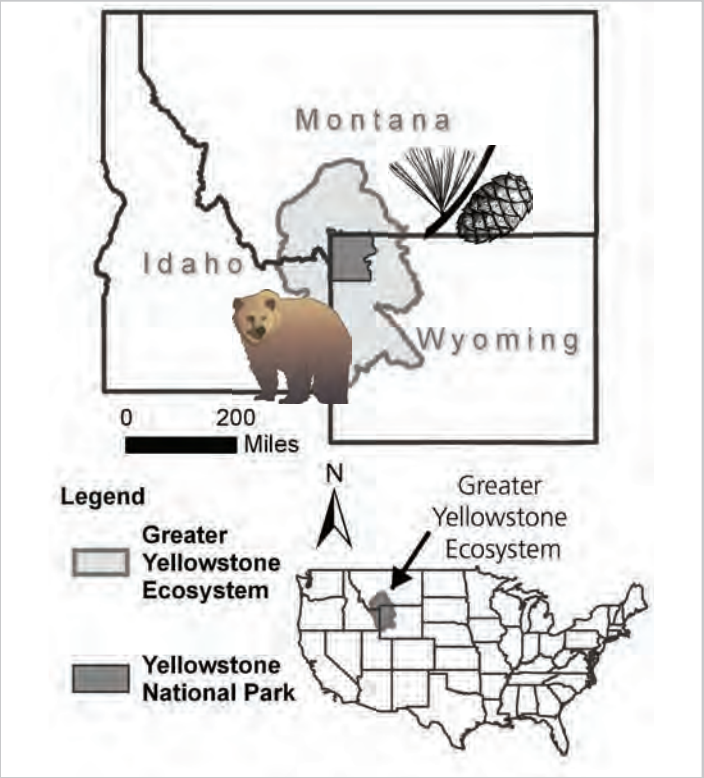
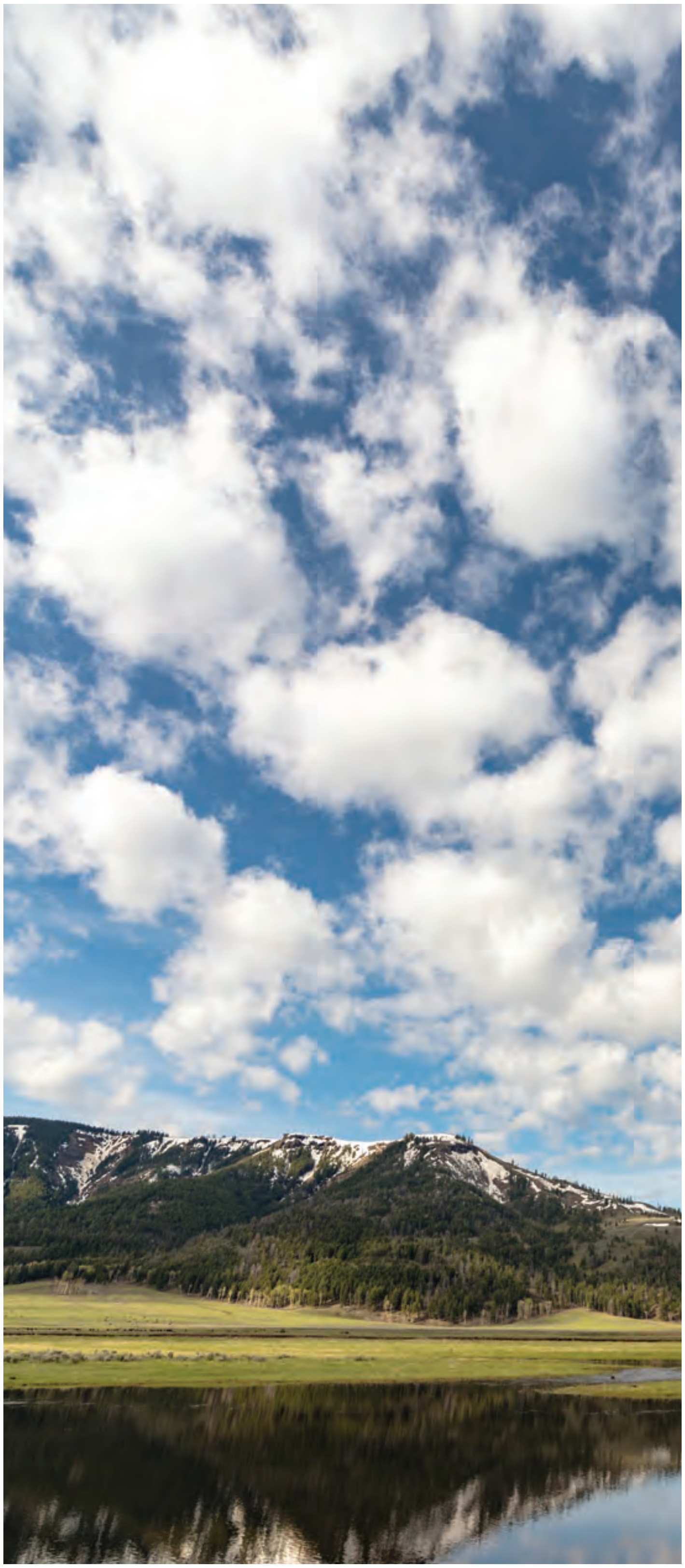


**Figure 1. Coordinated, long-term monitoring of grizzly bears and whitebark pine has helped to shape our understanding of the status of populations of these iconic species across the GYE. Grizzly bears and whitebark pine are the only non-game biological vital signs monitored across such a large part of the landscape. Images courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/)**

Long-term vital signs monitoring can have even greater value than short-term monitoring as it can result in a multi-decadal to multi-century window of scientific observations; observations critically needed to identify key drivers of



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ecosystem and biological community change that can be subtle or slow to unfold ("Past Warm Periods Provide Vital Benchmarks for Understanding the Future of the Greater Yellowstone Ecosystem" and "The Spatial Footprint and Frequency of Historic Snow Droughts in Yellowstone," this issue). Taken together, the benefits of long-term vital signs monitoring are numerous; moreover, the scientific and management communities recognize the value of long-term vital signs data sets for informing land management decisions and setting landmark environmental policy (Hughes et al. 2017).

## Vital Signs Monitoring in Yellowstone

In this issue, Legg and Haas ("Understanding Dynamic Ecosystems: the Pursuit of the Greater Yellowstone Network") describe the Greater Yellowstone Network's (GRYN's) Vital Signs Monitoring Program, one of 32 networks monitoring vital signs across the National Park Service. GRYN and other networks monitor vital park resources to document and continually update scientifically sound information on the status and long-term trends of park health (Fancy et al. 2009). Although consistency is a hallmark of monitoring programs, the articles in this issue also communicate why continued flexibility in monitoring approaches is a necessary part of successful long-term monitoring programs. Flexibility, in a monitoring sense, means embracing the use of emerging technological and statistical tools and regularly reevaluating the information needs of current and future park managers (Sergeant et al. 2012). Contributing authors to this issue also identify indicator groups that currently go unmonitored (e.g., insects; "Insects as a Vital Sign in the Greater Yellowstone Ecosystem," this issue) or are only informally monitored (e.g.,

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bats and aquatic plants; "Yellowstone Bats: an Important Indicator of Ecosystem Health" and "Aquatic Vascular Macrophytes as Vital Signs: Ecological Importance and Management Considerations for the Greater Yellowstone Ecosystem," this issue) and offer recommendations on establishing specific measurable objectives, share examples of existing protocols, and describe partnership opportunities ("Citizen Science Engagement: a Vital Part of Yellowstone Science," this issue) that would ensure the long-term success of a vital signs monitoring program for YNP and the region ("Assessing the Ecological Health of the Greater Yellowstone Ecosystem," this issue).

NPS I&M networks and partnering scientists rely on a number of sophisticated (e.g., "Patterns of Primary Production and Ecological Drought in Yellowstone," this issue) and traditional tools ("Invasive Plants as Indicators of Ecosystem Health" and "Taking the Pulse of Wetlands: What Are We Learning from the Amphibian Vital Sign?," this issue as examples) and techniques to monitor park vital signs and track ecosystem health. Collectively, these monitoring activities generate reams of data; however, scientists continue to grapple with the most effective ways to rapidly translate these data into information meaningful to resource managers (Schlesinger 2010) and, ultimately, management actions. Having long struggled with ways to translate timely medical data and discoveries from research universities to patients (i.e., from bench to bedside), medical practitioners now follow translational medicine practices. These translational practices focus on the "big picture" and consider the very best ways to leverage large data streams for practical patient-focused applications.

We argue that a similar kind of coordination and vision is needed to leverage the most relevant scientific discoveries and current vital signs data to impact park and ecosystem health by way of coordinated, structured decision-making in parks. Coordinated participation and open dialog between park managers, scientists, and stakeholders is already part of the culture at YNP; this "all hands on deck" approach will be crucial to interpreting change in vital signs, making sense of forecast data, and managing America's first national park during a period of rapidly accelerating human and climatic pressures (Hansen and Philips 2018). And just as patients can be passive recipients of medicine or medical treatments, patients can also play an active role if lifestyle choices are used to increase the chances of an improved health outcome. Similarly, park managers can be active participants in improving management outcomes through the judicious use of science-based prescriptions for ecosystem health.

## Forecasting Future Change

In the GYE and much of western U.S., snowpacks have declined considerably since the 1980s (Pederson et al. 2011; "The Spatial Footprint and Frequency of Historic Snow Droughts in Yellowstone," this issue). Long-term monitoring data collected by Natural Resources Conservation Service Snow Telemetry (SNOTEL) stations has significantly contributed to our understanding of temperature induced changes to snowpacks. These weather stations also contribute significantly to parameterization of global climate models that aid in forecasting future changes in YNP's snowpacks. In a recent summary, Tercek and Rodman (2016) modelled changes to YNP's future snowpacks with a goal of better understanding how these changes are likely to affect oversnow travel along the park's major road corridors. Increasingly winter recreation including oversnow travel on park roads contributes to the regional economy (Hamming 2016); therefore, this work has important implications for establishing future travel policies. By the end of the century, winter snowpacks are likely to decline throughout the park. However, the most significant reductions in drivable snowcoach tourism would be felt along the park's west entrance (Tercek and Rodman 2016; figure 2). Long-term vital signs monitoring of precipitation and temperatures have contributed to the development of snowpack forecasts and support predictions of future change. In this issue, Tercek ("Nowcasting and Forecasting Fire Severity in Yellowstone") employs climate models based on vital signs data to forecast future changes in fire frequency and intensity.

## The Vital Sign Special Issue

The articles included in this special issue emphasize why business-as-usual science, separate and apart from long-term monitoring and park decision-making, is no longer sufficient for managing complex park ecosystems through an era of rapid environmental change (National Park System Advisory Board Science Committee 2012). Instead, coordinated monitoring approaches between scientists, stakeholders, and decision makers with clear, mutually-defined goals and sustained financial commitments are needed to support

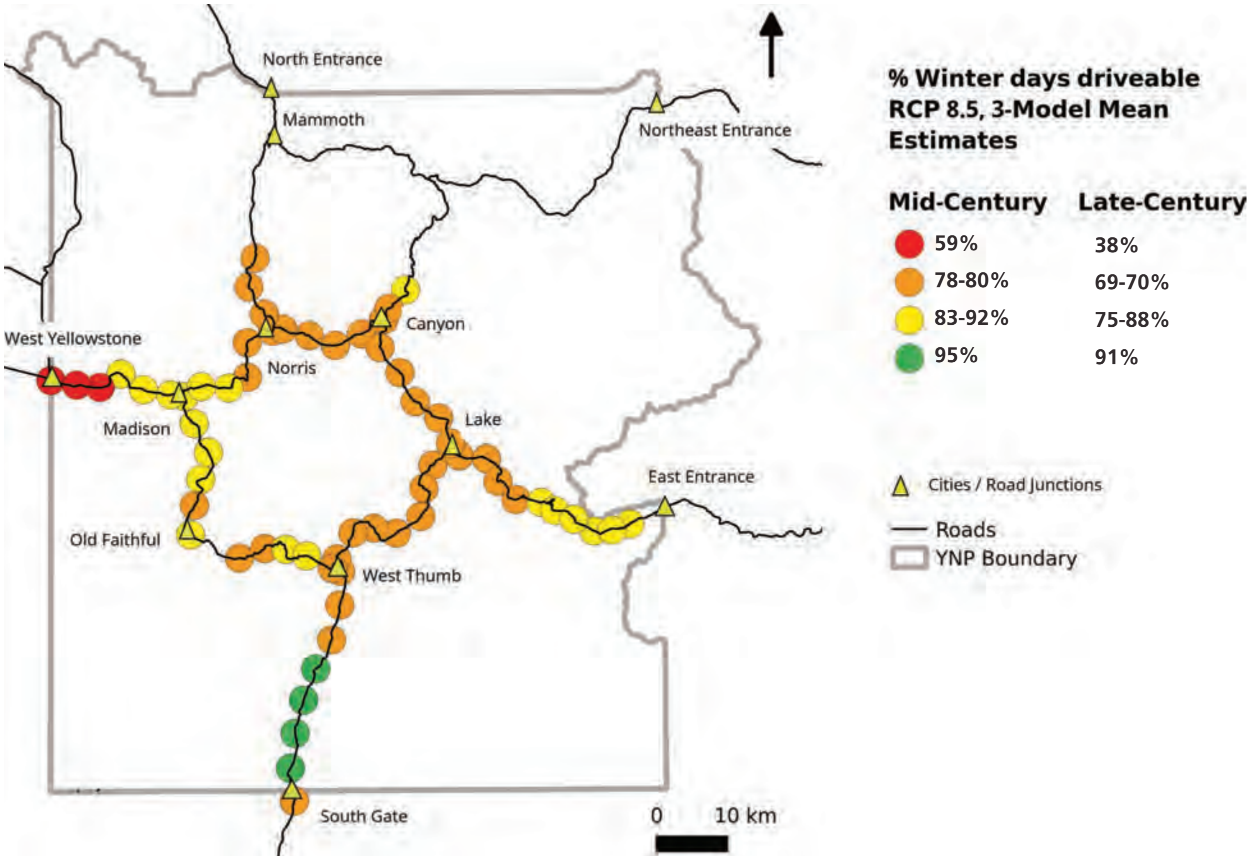

**Figure 2. Mapped winter driveable days forecasted for the period December–March that will be "oversnow driveable" and using Representative Concentration Pathway (RCP) 8.5 forecasts. RCP forecasts represent scenarios for carbon dioxide emissions trajectories, and the 8.5 scenario is one where emissions continue to increase unchecked through the early and mid parts of this century. The percentages shown are averages of driveability using 3 models (see Tercek and Rodman 2016 for more details). Since the percentages shown in this figure are multi-model averages, they do not include the most extreme forecast for any location. For example, the single model forecast with the greatest snow losses for red points shown on the west entrance road was just 29% driveability by late century. (Originally published at: https://doi.org/10.1371/journal.pone.0159218.g013.)**

robust and informative long-term vital signs monitoring programs. These vital signs monitoring programs will be key to exploring and describing how modern stressors like exurban development, novel diseases ("The Yellowstone River Fish-Kill: Fish Health Informs and Is Informed by Vital Signs Monitoring," this issue), the establishment and spread of invasive species, increased recreation, and climate change interact (Enquist et al. 2017). These types of programs are also uniquely positioned to provide a mountain top view of complex ecological conditions for decision makers and serve as underpinnings for a shared and fact-based understanding of ecosystem health, a foundation for establishing sound policies, and a catalyst for partner and public engagement.

> *Scienceless decisions are the fastest way to the impairment of NPS resources.*
>
> **– Cameron Sholly, Superintendent Yellowstone National Park, July 17, 2018, *Mountain Journal***

This issue of *Yellowstone Science* highlights the importance of vital signs monitoring that informs park condition by putting up-to-date information in appropriate context and offers clear examples of how vital signs data can be marshalled to address some of the most pressing management issues. Never before have we had access to so much information on physical vital signs (e.g., climate, river flow) via technology. Biological data offering historical context, however, is far less common but increasingly necessary for understanding population health, characterizing long-term change, and forecasting future change. Today scientists are explicitly linking physical (e.g., snow, temperatures, and moisture deficit) and biological vital signs. The responses of biological indicators (see Ray et al. 2016, Shanahan et al. 2017; "Patterns of Primary Production and Ecological Drought in Yellowstone," this issue) define the sensitivity of biological vital signs to past change and support forecasts of impending change.

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Although Fredrick Turner's early studies provided a unique historical backdrop for the evaluation of the spotted frog population at Lodge Creek, we don't yet know from this isolated study how spotted frogs throughout YNP or the GYE have fared. Follow-up surveys at Lodge Creek in the 1990s documented a dramatic decline of the historic population at Lodge Creek (Patla and Peterson 1999). While follow-up surveys could not undo spotted frog declines, the Lodge Creek case study served as a launch point for annual, parkwide amphibian monitoring efforts and a more comprehensive and scientifically defensible vital signs monitoring campaign for YNP. Modern advances in statistics and modeling support determinations of causation and forecasting at scales that were hardly possible in Turner's time and without parkwide and regional monitoring efforts. The benefits of these ongoing monitoring efforts are difficult to fully assess today, but this monitoring will serve as an enduring resource and foundation for future, currently unimaginable, science and the basis for data-driven decisions for generations to come.

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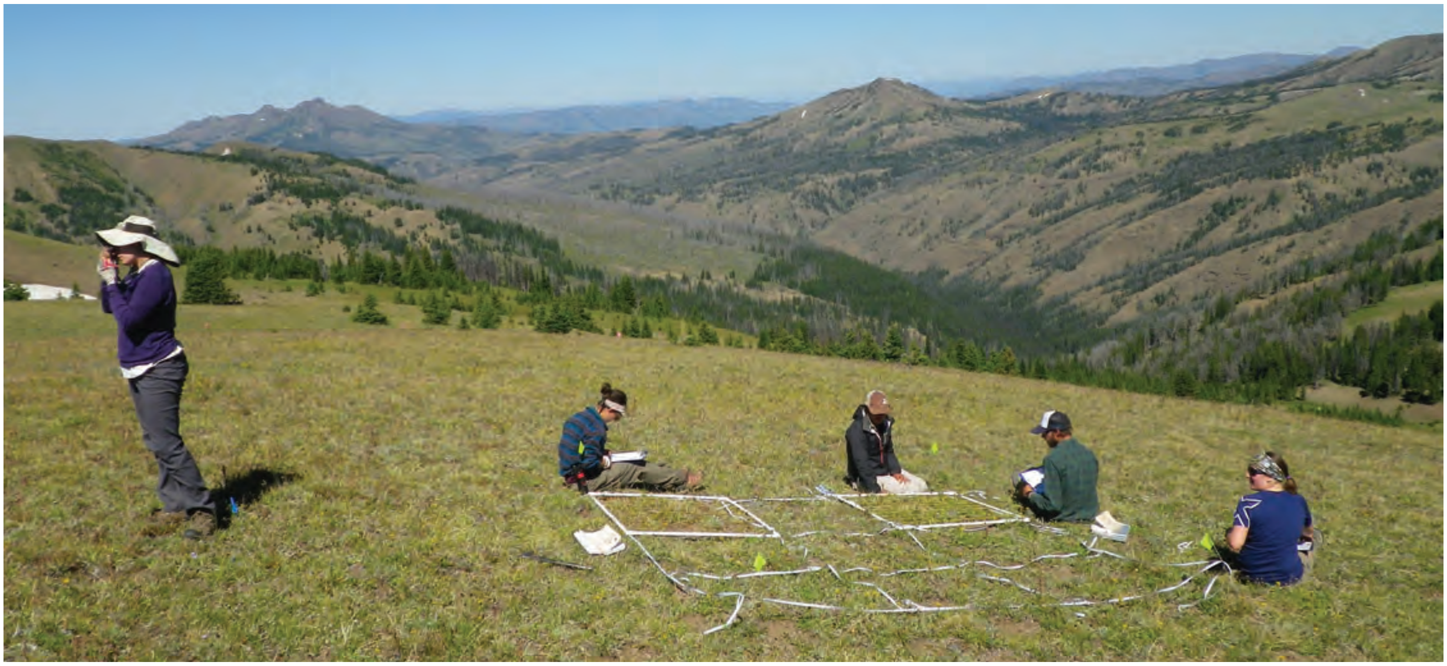
# Understanding Dynamic Ecosystems: The Pursuit of the Greater Yellowstone Network

*by Kristin Legg & Sarah Haas*

> We cannot protect what we do not understand.
> — NPS Natural Resource Challenge, 1999



**In 2016, a field crew collects alpine vegetation data at the long-term monitoring site located in the Absaroka Range along the east boundary of Yellowstone National Park. We study how plants, soils, and climate data change over time in order to understand how alpine areas are responding to climate change. This monitoring program is part of a larger global effort led by the Global Observation Research Initiative in Alpine Environments (GLORIA; gloria.ac.at).**

## Who Are We?

The year 1999 was a pivotal year for the National Park Service (NPS). Inspired by the book *Preserving Nature in the National Parks: A History* (Sellars 1997), the Natural Resource Challenge (NPS 1999) was crafted to expand the NPS's understanding and management of park natural resources. One of the more innovative outcomes of the Natural Resource Challenge was the creation of the NPS Inventory and Monitoring (I&M) Program. The overall mission of this program was to first establish a baseline inventory of park natural resources (**What do we have?**) and second, to provide scientifically sound information on how select resources are changing through time (**How are parks doing?**). This ongoing program is intended to provide the scientific basis for knowledge, management, and education about park resources and a view of the park ecosystems not previously available (Fancy et al. 2009). The I&M Program's natural resource targets are intentionally wide ranging to include focal species (e.g., whitebark pine), taxonomic groups (e.g., bats, amphibians, birds), physical resources (e.g., water quality and quantity), natural ecosystems and associated communities (e.g., caves, marine areas, forests), and environmental drivers (e.g., climate).

The architects of this program recognized the benefit of grouping parks that are similar ecologically and geographically near one another, so that teams of NPS scientists, park managers, and partners could develop rigorous and relevant multi-park, long-term monitoring programs. As a result, 32 ecoregional networks were created to support over 280 parks with diverse and significant natural resources. As envisioned, each network collaborates among a group of parks to implement actions and take advantage of economies of scale. The Greater Yellowstone Network (GRYN), one of the 32 networks, is comprised of Bighorn Canyon National Recreation Area, Grand Teton and Yellowstone national parks, and the John D. Rockefeller, Jr., Memorial Parkway.

## What Do We Have?

Similar to the other networks, the GRYN initially focused on baseline inventories of 12 targeted natural resource categories (e.g., air quality, water resources, vertebrate and plant species, geologic processes and features, soil resources, etc.). These inventories have been useful in advancing the parks' and the public's understanding of species present, as well as the state of air and watershed quality, among other resources. These inventories also serve as a foundation for how future changes to a park may affect long-term conservation of critical resources. These baseline inventories were used to inform the vital signs selected for long-term monitoring—the second phase of the network goals (see "Vital Sign Monitoring is Good Medicine for Parks," this issue, for the definition of "vital signs").

## How to Select a Vital Sign?

It is a daunting task to select just a few of a park's diverse natural resources to study long into the future. Working in collaboration, the GRYN, park managers, scientists, and partners prioritized natural resources using three criteria: ecological significance, management significance, and legal or policy mandates as directed from Congress or other legislation (Fancy et al. 2009). While staying true to the concept of an ecological network, GRYN and collaborators selected a subset of 48 identified vital signs for long-term monitoring (Jean et al. 2005). Yellowstone staff monitor at least 27 of the identified vital signs, including trumpeter swans, earthquakes, ungulates, raptors, and native fish. The GRYN focuses on seven vital signs based on what can realistically be monitored annually, while maintaining the necessary rigor required to reliably detect temporal change.

### Greater Yellowstone Inventory & Monitoring Network

The GRYN leads, in collaboration with the parks, the long-term monitoring programs for alpine vegetation, amphibians and wetlands, climate, land use change, upland sagebrush steppe, water resources (quality and quantity), and whitebark pine. More about the network and each of these vital signs are on its website:

www.nps.gov/im/gryn

Another visionary part of the I&M Program is the emphasis placed on data stewardship and information sharing, critical components of long-term environmental monitoring that maximizes utility and learning (Lovett et al. 2007, Fancy et al. 2009). The value of long-term monitoring data is often under-appreciated initially, but its importance is later realized years down the road. Valuable and notable records include century-old weather station data collected by park managers, which are now used to help understand how climate is changing in the parks. By integrating weather data with monitoring data of small mammal populations in Yosemite National Park, park managers learned that small mammals had shifted upward in elevation in response to warming temperatures (Moritz 2007). Long-term monitoring can also help us anticipate and prepare for future changes to park ecosystems. For example, the monitoring of $CO_2$ concentrations a top Hawaii's Mauna Loa volcano has proven invaluable in numerous ways, but principally in connecting global temperature changes to rising $CO_2$ levels. When this monitoring was initiated, there was no way to know it would someday serve as one of the most valuable scientific geophysical records ever collected. Over 60 years later, the "Keeling Curve" is a vital sign for Earth health (Keeling 2008; https://scripps.ucsd.edu/programs/keelingcurve/2013/04/03/the-history-of-the-keeling-curve/). Imagine what scientists of the future will learn from the vital sign records collected in the parks today.

To help us oversee these important data, each park vital sign has a scientifically designed protocol, or recipe, that describes the collection, stewardship, analysis, and reporting of data needed to meet targeted objectives and ensure long-term consistency over time. The emphasis on data management and use of scientific protocols is one of the program's greatest strengths in ensuring that we can provide timely, high quality science to parks and the public. Results are used to inform management decisions and lead to a greater understanding of long-term or emerging trends in each park's dynamic ecosystems.

## How Are Parks Doing?

In partnership with the parks and partners, GRYN has contributed to park stewardship of natural resources since 2000. For example, timely and targeted water quality monitoring informed the Montana Department of Environmental Quality that Soda Butte Creek, a tributary

NPS PHOTO - D. RENKIN

to the Lamar River in the northeast corner of Yellowstone National Park (YNP), could be removed from the list of impaired waters (i.e., 303(d) list) following the reclamation of an abandoned mill and tailings site (Henderson et al. 2018). The status and trends of whitebark pine across the Greater Yellowstone Ecosystem ("An Uncertain Future: The Persistence of Whitebark Pine in the Greater Yellowstone Ecosystem," this issue) has contributed to the region-wide whitebark pine conservation strategy (GYCCWPS 2011) and were informative for the U.S. Fish and Wildlife Services' review of whitebark pine during a status assessment for the Endangered Species Act. The GYA whitebark pine monitoring program has also been held up nationally as a leading example of how to track whitebark pine and other five-needle pines. The amphibian and wetland monitoring program is one of the largest (geographically) and longest running monitoring campaigns in the western U.S. It is providing critical information to improve our understanding of amphibian population dynamics and their responses to climate-induced habitat loss ("Taking the Pulse of Wetlands: What Are We Learning From the Amphibian Vital Sign?," this issue). We are integrating climate vital signs with biological indicators to better understand when changes in natural resource conditions should be anticipated ("Patterns of Primary Production and Ecological Drought in Yellowstone," this issue). In partnership with YNP's vegetation program, sagebrush and grassland monitoring will help inform the park on the health of sagebrush grasslands (see the next issue of *Yellowstone Science* focused on grazing). The Yellowstone Dashboard on the Climate Analyzer website (www.climateanalyzer.org/) offers managers and the public easy access to weather station and stream flow data. Importantly, this tool provides users information in formats that quickly supports year-to-year comparisons of ecosystem processes like snow cover and snow melt runoff. In addition, YNP relies on vital signs data to inform park planning and publications such as the annual *Resources & Issues Handbook* and the Vital Signs and State of the Park resources reports (YCR 2011, 2013, 2018). Researchers also frequently contact the network to collaborate on projects and access vital signs data to help answer questions on the park's ecosystem health.

Yellowstone is not alone—NPS I&M networks across the country continue to demonstrate the value of long-term monitoring in parks. In the Pacific Islands, monitoring data helped determine where and when to remove crown of thorns sea stars that were threatening coral reefs (Brown et al. 2017). Monitoring of forests in dozens of eastern U.S. parks revealed significant differences in forest structure (e.g., older and larger trees, more standing dead material, and different disturbance dynamics) relative to surrounding forests (Miller et al. 2016). These articles were featured in a special issue of the scientific journal *Ecosphere* (Rodhouse et al. 2016) that highlighted inventory and monitoring science as part of the 2016 NPS Centennial.

After nearly two decades, the vision of those who led the 1999 Resource Challenge and advocated for natural resource inventories and vital signs monitoring in parks is being achieved in tangible ways. NPS I&M networks are helping to tell the stories of important ecosystem functions. In the GYA, the GRYN illuminated landscape-level change in whitebark pine stands, participated in efforts to steward the Soda Butte Creek watershed to better health, and improved our understanding of how environmental drivers like changing snowpack may result in fewer wetlands for amphibian breeding. Through the continued collaboration with park managers, scientists, partners, and the public, vital signs monitoring will support science-based decision making into the future, paramount to the long-term conservation of park resources.

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While working in Yellowstone, **Kristin Legg** distinctly recalls hearing about the Inventory and Monitoring Program in 1999 and dreamt of being part of that program. This became a reality in 2010 when she became the program manager for the Greater Yellowstone Network. Prior, she was the Chief of Resource Management & Science at Zion and Bryce Canyon national parks and Pipestone National Monument. Kristin received an MS in Fish & Wildlife Management from Montana State University.

**Sarah Haas** is currently the Deputy Chief of Science & Resource Management at Grand Canyon National Park. She worked for several years in Yellowstone's Center for Resources as the Science Program Coordinator, as well as Deputy Chief. Sarah has worked with a variety of species on the edge of existence and considers it her primary responsibility to promote the understanding and conservation of the biodiversity of our national park treasures.

# Assessing the Ecological Health of the Greater Yellowstone Ecosystem

### *Andrew M. Ray, David P. Thoma, Kristin L. Legg, David M. Diamond, & Andrew J. Hansen*

Species declines and extinctions are occurring at rates that are unrivaled in human and geological history (Ceballos et al. 2017). Similarly, wild places are also dwindling in area (Watson et al. 2018). Some large, protected areas like the Greater Yellowstone Ecosystem (GYE; figure 1) have experienced less change than more populated corners of the world primarily because the GYE benefits from a substantial level of federal agency protection. This 22 million acre-ecosystem with Yellowstone National Park (YNP) at its core represents continuous essential habitat for sustaining a viable population of free-roaming grizzly bears (Craighead 1977).

In the GYE, nearly two-thirds of the lands are managed by federal agencies that use techniques designed to achieve or maintain public land health for the benefit of future generations. Coordinated, cross-boundary conservation efforts in the GYE have captured the attention of conservationists the world over. Grizzly bear populations have grown from approximately 150 in 1975 to over 700 bears today (van Manen et al. 2018). Wolves were reintroduced to YNP between 1995 and 1997; and despite higher human-caused mortality outside of the national park boundaries, wolves are now widespread throughout the GYE (Smith et al. 2016). Native fish restoration efforts are helping to protect cutthroat trout and grayling strongholds through targeted non-native species eradications (Koel et al. 2017), and states are helping to bring together public and private stakeholders to establish landmark protections for antelope, elk, and mule deer migration corridors (WYGFD 2016).

Despite these successes and the strategies used by land managers to maintain the health, diversity, and productivity of public lands, other stressors still loom large. Some of the threats are historic (e.g., legacy pollution from mining), but many, including climate change, exurban growth, increased recreation, invasive species, and wildlife disease represent modern stressors with limited historical influence for contemplating outcomes or mitigative actions (Hansen et al. 2014). Even on the most protected lands in the GYE, where human pressures have been quite modest (27.5% of the GYE is managed as wilderness), these external stressors have already contributed to significant changes including rising temperatures, changes in snowpack, and the introduction and expansion of invasive species. These changes have produced new mixtures of native and invasive species growing and living under new rules with rapidly changing environmental conditions. The collection of new conditions and species assemblages are typically referred to as novel ecosystems (Hobbs et al. 2006.)

On the private lands' portion of the GYE, land use, climate change, and invasive species are similarly pushing ecosystems towards unfamiliar conditions. Taken together, these documented changes and the anticipation of future conditions across the GYE will require shifts away from historical management approaches and towards novel

**Figure 1. Map of the GYE showing land ownership.**

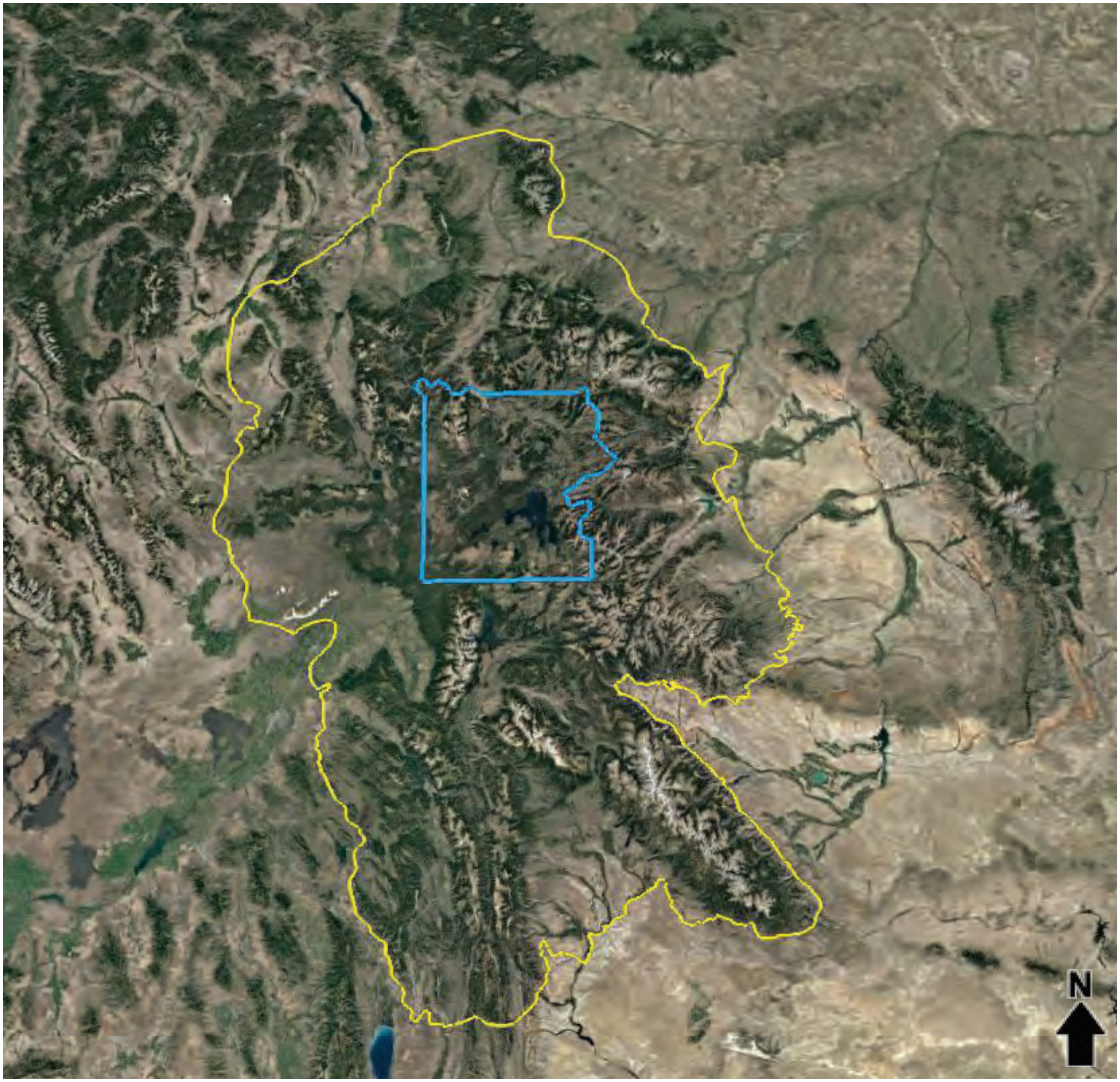

**Figure 2. Satellite image of the GYE showing variations in vegetative productivity (i.e., greenness) across the ecosystem. The GYE boundary is shown in yellow and, for reference, the YNP boundary is shown in blue. Imagery is from the National Aeronautics and Space Administration (NASA).**

management strategies and deliberate adaptation planning (e.g., Climate Smart Conservation and Scenario Planning; Stein et al. 2014). Understanding how to manage these new ecosystems, therefore, requires documentation of how conditions are changing.

To characterize the sometimes messy and individualized details of ecosystem change (Rodhouse et al. 2016), we need vital signs monitoring that is tailored to the specific needs of the region. An integrated, cross-organizational, GYE-wide vital signs monitoring and assessment program is essential for characterizing local and regional conditions (e.g., patterns in biological productivity at scale; figure 2) documenting past biological, chemical, and physical change, and to help us perceive problems before they become intractable. Documenting conditions is also a critical first step to contemplating whether traditional or novel management strategies will be needed to achieve management goals of desired future conditions (Seastedt et al. 2008, Truitt et al. 2015).

A regional framework already exists for monitoring a number of the GYE's physical vital signs (e.g., Sepulveda et al. 2015, Al-Chokhachy et al. 2017). For example, weather conditions, snowpack depths, and river flows across the GYE are already being monitored through a network of stations that regularly transmit publicly available measurements. As a result, the monitoring of regional air temperatures, snowpacks, and river and stream flows (physical vital signs) can be readily summarized and compared against a historical backdrop. And as the country's oldest national park, some of YNP's vital sign records (e.g., air temperature and river flow data) in the GYE span the 20th century.

On the other hand, coordinated efforts to monitor non-game biological indicators at a comparable spatial scale are less common (grizzly bears and whitebark pine are notable exceptions). Scaling existing biological vital signs monitoring programs that are already underway in YNP and neighboring Grand Teton National Park (e.g., amphibians and bats) or developing protocols for monitoring species and taxonomic groups that are informally monitored (e.g., butterflies) or currently go unmonitored would require financial and personnel resources that currently do not exist. Despite these limitations, the need to track changes in abundance and distribution of biological indicators and, more generally, ecosystem health are widely embraced (Fancy et al. 2009, Rodhouse et al. 2016).

To add value to the monitoring data, it is important to analyze trends in ecological condition over recent decades and to project possible trends under plausible future scenarios. Such analyses allow for establishing if vital signs are improving relative to management objectives, are stable, or are deteriorating, thereby providing a basis for prioritizing management actions (Hansen and Phillips 2018). It is also important to effectively communicate these trends to the diverse stakeholders of the GYE so they have information to inform decision making about actions relevant to the health of the GYE.

In "Vital Signs Monitoring is Good Medicine for Parks," this issue, we learned that knowledge gained through human health monitoring is beneficial for establishing individual baselines or reference points, supporting diagnoses, initiating medical interventions, surveilling diseases, and characterizing health responses to medical treatments. Comparable benefits can be achieved from monitoring ecosystem health, and the knowledge gained should support informed stewardship of GYE's public and private lands.

A monitoring program with clearly defined objectives and statistically valid design offers clear benefits over more piecemeal or reactive data gathering activities (Lindenmayer and Likens 2018). For example, a regional monitoring program will help prioritize limited resources, identify solutions to the most pressing of the GYE's ecological problems (e.g., connectivity, refugia, blister rust resistant trees), raise awareness of issues so they get needed attention, and offer a sharper understanding of the scale of the ecological impacts. In sum, a well-thought-out, well-planned monitoring program will ensure that the right actions can be implemented in the right place and at the right time.

We all have a stake in preserving and protecting YNP and surrounding public and private lands that constitute the GYE. Without information generated through monitoring, we have limited knowledge about how, where, and when conditions are changing. For a region recognized as one of Earth's remaining intact wildlands, we argue that a greater understanding of the health of the GYE (gained through monitoring) is worth considering. The knowledge gained would, in turn, serve as essential underpinnings for future policy and a catalyst for public engagement (Brandt et al. 2014). Regardless of what management or adaptation strategies are ultimately adopted, a regional vital signs monitoring program will be an indispensable component of protecting and preserving YNP and the region (Hansen and Phillips 2018).

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**Andrew Ray** (see inside cover), **David Thoma** (see page 11), **Kristin Legg** (see page 17)

**David Diamond** (left) is the Executive Coordinator of the Greater Yellowstone Coordinating Committee (GYCC). Through the GYCC, federal land managers pursue voluntary opportunities to cooperate at the landscape scale (see https://www.fedgycc.org/). David's federal experience includes work with the National Park Service, National Oceanic and Atmospheric Administration, the U.S. Fish and Wildlife Service, and the Department of the Interior. David has a Master of Science in Environmental Science and Master of Public Administration from the School of Public & Environmental Affairs at Indiana University, and a bachelor's in environmental science and history from the University of Virginia.

**Andrew Hansen** (right) is a Professor in the Ecology Department and Director of the Landscape Biodiversity Lab at Montana State University. He teaches macroecology to undergraduates and landscape ecology to graduate students. His research focuses on interactions among biodiversity, climate change, and land use, with an emphasis on large landscape management and protected areas. He received a Ph.D. in ecology at the University of Tennessee and the Oak Ridge National Laboratory. He was on the faculty of Oregon State University, where Dr. Hansen studied ecological approaches to forestry. Current research at Montana State University focus on sustaining wildland ecosystems under climate and land use change, with a focus on the US and eight countries in the humid tropics. This work uses a combination of remote sensing, spatial analysis, computer simulation and field studies. This research has been funded primarily by NASA, US Department of the Interior, Environmental Protection Agency, US Department of Agriculture, conservation organizations, and the timber industry. Dr Hansen currently is on the science leadership teams for the North Central Climate Science Center and the Montana Institute of Ecosystems. He is co-editor of the recent book, "Climate Change in Wildlands: Pioneering Approaches to Science and Management.

# The Spatial Footprint and Frequency of Historic Snow Droughts in Yellowstone

### *by Bethany L. Coulthard, Gregory T. Pederson, & Kevin J. Anchukaitis*

In the face of climate change and increasing human pressures, monitoring and characterizing environmental change is increasingly important in national parks and protected areas (Hansen and Phillips 2018). Regional measurements of snowpack are a critical vital sign (see "Vital Signs Monitoring is Good Medicine for Parks," this issue) both for monitoring ecosystem health and anticipating future water availability. Snowpack represents accumulated cool-season water storage that, if kept cool, is slowly released as summer meltwater which maintains ecosystems and replenishes reservoirs that sustain society. Western snowpacks have been shrinking since around 1950 due to warmer temperatures resulting from human-caused climate change (Fyfe et al. 2017). Future climate projections indicate this trend will continue throughout the 21st century (Mankin and Diffenbaugh 2015). In Yellowstone National Park (YNP), deep snowpacks and subsequent meltwaters contribute substantially to the flow of the Missouri, Colorado, and Columbia rivers, making a "snow drought" or period of abnormally low snowpack in this region a serious threat to ecosystems and water supplies for much of the West (Tercek et al. 2015).

## Multi-year Snow Droughts: How Often and How Long Can They Last?

Two important questions for water managers, ecosystems, and communities are: "how many years can snow droughts last?" and "how often do multi-year snow droughts happen?" A good example of why this is important is the recent multi-year drought (2011-2016) in California that resulted in the over-extraction of groundwater, agricultural irrigation restrictions, and hydroelectricity cutbacks. Ultimately, the drought culminated in an unprecedented statewide water use restriction (Mann and Gleick 2015). A single snow drought year can often be managed through using water stored in major reservoirs, but multi-year snow droughts become increasingly challenging as banked water supplies are depleted (Mote et al. 2018). In this article, we address the question: how long have snow droughts historically lasted in Yellowstone?

Multi-decadal snow measurements like those recorded across the United States by the Natural Resources Conservation Service (NRCS) Snow Telemetry (SNOTEL) and snow course networks are the main resource for understanding changing snow dynamics. However, these relatively short observational records typically around 30-40 years for SNOTEL records or 60 to nearly 100 years for the longest snow course records only capture a few multi-year snow drought events. Our understanding of the natural frequency and severity of snow droughts from such short records is therefore limited. This, in turn, restricts our ability to contextualize recent and likely future snow drought events.

## Tree Rings Measure Snow Droughts Over Space and Time

One approach to answering questions about past snow droughts is by using snow-sensitive tree-ring records, which are increasingly being capitalized upon to reconstruct historical snow dynamics (Belmecheri et al. 2016, Pederson et al. 2011, Woodhouse 2003). Snow sensitive trees in the U.S. West tend to exhibit two types of growth responses, those whose growth benefits from snow meltwater (typically growing in low to mid-elevations) and those whose growth is inhibited by deep and late-lying spring snowpack (typically growing at high elevations). These growth responses are recorded at the stand (or population) level from numerous species and can provide annual historical records, or "reconstructions", of year-to-year snow variability going back centuries and even millennia. Tree-ring based snowpack reconstructions have already provided important insights about past snow dynamics in YNP regarding the influence of modern temperature increases on snowpack declines, and the recent widespread and synchronized spring snowpack declines since the 1980s along the Rockies (Pederson et al. 2011). Here we present a set of new snowpack reconstructions for YNP that offer enhanced spatial resolution (4 km$^2$ grid versus large watersheds) and have been extended in length (beginning in AD 700 compared to AD 1200) relative to the original Pederson et al. (2011) reconstructions. We use these new spatially gridded snowpack reconstructions to identify and map YNP's past severe multi-year snow drought events.

The new reconstructions are unique in that they are spatially gridded, which allows us to examine snow drought

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events over both space and time. Using a gridded spatial field reconstruction approach (Point-by-Point Regression; see Cook et al. 2004), each individual gridpoint is reconstructed and represents its own multi century- to multi millennia-long snow moisture (snow moisture is expressed as snow water equivalent or SWE) reconstruction describing local, yearly snow levels and spanning the age of available tree-ring records. We used a 2.5 mi x 2.5 mi (4 km x 4 km) gridded modeled snow moisture dataset (see Hostetler and Alder 2016) and a large network of more than 500 curated, snow-sensitive tree-ring records (i.e., chronologies) in our analysis. Snow moisture content or SWE data as measured on April 1st of each year was used since it historically serves as a reliable estimate of maximum cool-season snow water content, which is directly relevant to forecasting spring runoff and warm-season water supply. The final reconstruction model was employed over the length of available tree-ring records to provide annual estimates of local, gridpoint snow moisture (i.e., SWE) back through time. Further methodological details can be found in Cook et al. (2004).

## A 1300-year Gridded Snowpack Record for Yellowstone

The top panel in figure 1 shows a plot of reconstructed mean snow moisture (in mm of SWE) for YNP (the average of all gridded reconstruction means from YNP). Similar to a reconstruction by Pederson et al. (2011) developed specifically for the Greater Yellowstone Region (GYR), this record highlights unusually low snow moisture (SWE) during the early 1500s, during the 1930s dustbowl, and at the turn of the century drought in the 2000s. This longer record, however, also documents unusually low snow moisture conditions in YNP during the mid-700s and in AD 1014.

## Notable Major Snow Drought Events

The bottom panel in figure 1 shows maps of gridded average reconstructed snow moisture during known historical snow droughts, demonstrating the utility of the gridded tree-ring records to provide spatially relevant information on snow moisture conditions of the past. The ability of the

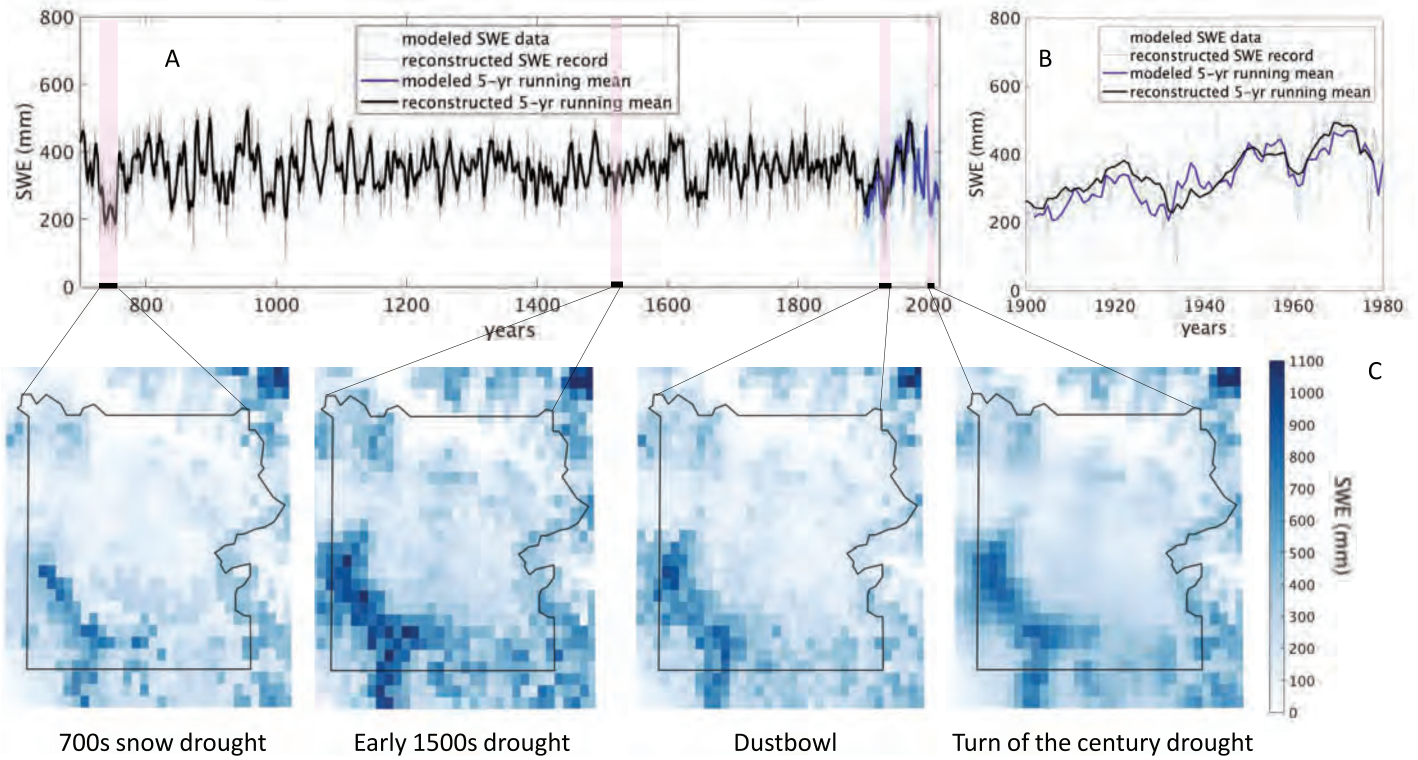

**Figure 1. (A) Time plot of average reconstructed April 1 snow moisture (expressed in mm of SWE) for YNP (grey line) with 5-year running average (black line) and average modeled SWE data for YNP (light blue line) with 5-year running average (blue line); historical periods of interest are highlighted in pink. (B) Modern (1900-1980) time plot of the model with the same datasets and line colors as in A. (C) Maps of gridded average reconstructed snow moisture during historical periods of interest in YNP. From left to right: 700s snow drought (AD 730-750), early 1500s drought (AD 1511-1530), dustbowl drought (AD 1929-1936), and the turn of the century drought (2000-2010; data for this recent drought is from the modeled, not reconstructed, SWE record).**

reconstructions to faithfully record known historical events like the 1930s dustbowl drought is a useful check on the model accuracy, while the spatial fingerprint of pre-historic snow droughts in the 700s and early 1500s can also be examined. Notably, the early 1500s were wetter in YNP than across the GYR, and SWE deficits during the 700s appear more severe than other major pre- and post-industrial snow droughts in YNP and the across the region.

## The Frequency of Multi-year Snow Droughts

To identify multi-year snow droughts in YNP we conducted an analysis (see González and Valdés 2003) on the reconstructed April 1 snow moisture data. We defined a snow drought year as a reconstructed SWE value below the 25th percentile or value below the lowest 25 percent of observations for the entire reconstruction. We also calculated how many snow droughts occurred at each grid point, testing all possible snow drought-lengths from one year long to twelve years long. For snow droughts greater than three years long, a single year of high snow moisture (i.e., SWE ≥25th percentile) was not permitted to interrupt a multi-year snow drought. This was done because a single year of above average snow moisture is often not sufficient to replenish stored water at major reservoirs during a multi-year snow drought from a water resource management perspective.

The maps in figure 2 show the number of 3- to 12-year long snow droughts in YNP over the past 1,300 years. Almost the

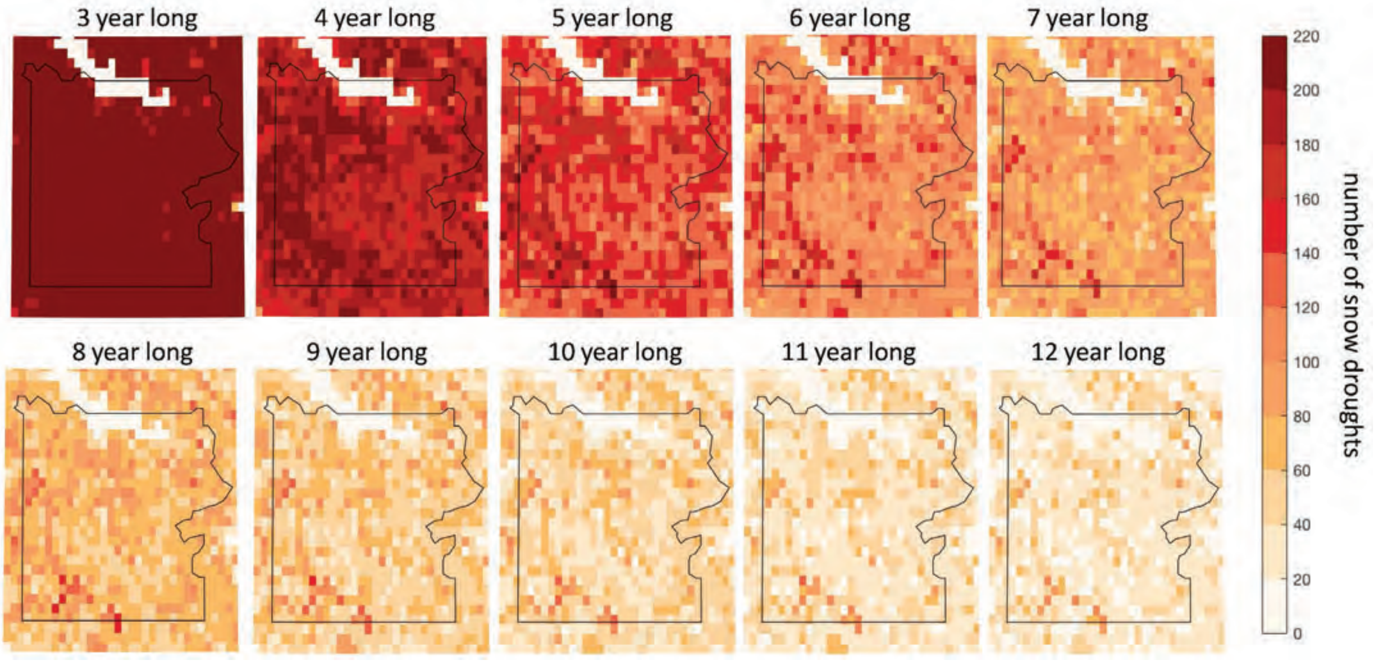

**Figure 2. Maps of the Yellowstone area showing the total number of different-length snow droughts since AD 700 as calculated from gridded, tree-ring based snow moisture reconstructions.**

entire region has experienced more than 200 three-year snow droughts in this time. In other words, during a total of ~190 years of the 1,300-year reconstructed record, YNP was in a three-year snow drought. Longer snow droughts are also more common in YNP than has been previously recognized. Beyond known decadal-scale droughts like the dustbowl, tree-ring records suggest most of YNP has experienced between one and forty 12-year long snow droughts since AD 700. Considering all of the snow droughts identified in this analysis, 37% lasted between 3 and 6 years, and 16% lasted between 7 and 12 years. Note that to provide a complete picture of both short and long snow droughts that occur in YNP, shorter droughts contained within longer droughts were counted as events in this analysis. These findings indicate long and persistent snow droughts were a natural part of the snowpack system in YNP during the pre-industrial era. Such droughts could have serious consequences for water supply and natural resource management in YNP, especially when exacerbated by the host of other water-related and ecological changes that are likely with continued warming.

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# Nowcasting & Forecasting Fire Severity in Yellowstone

*by Mike Tercek*

## Fire Severity is Increasing

Climb any mountain in the spring, and you will find that Yellowstone National Park (YNP) is made almost entirely in shades of green. Many grayish-blue peaks encircle the far horizon; but in the park itself, only a few nunatak mountains push up pinpoints of bare rock. Thick, green forests cover 80% of the landscape. Grassy valleys and sagebrush fill in most of the rest (Despain 1990). Yellowstone is defined by its plants. Most of Yellowstone's scenery—and habitat—is the result of a living, green adaptation to fire.

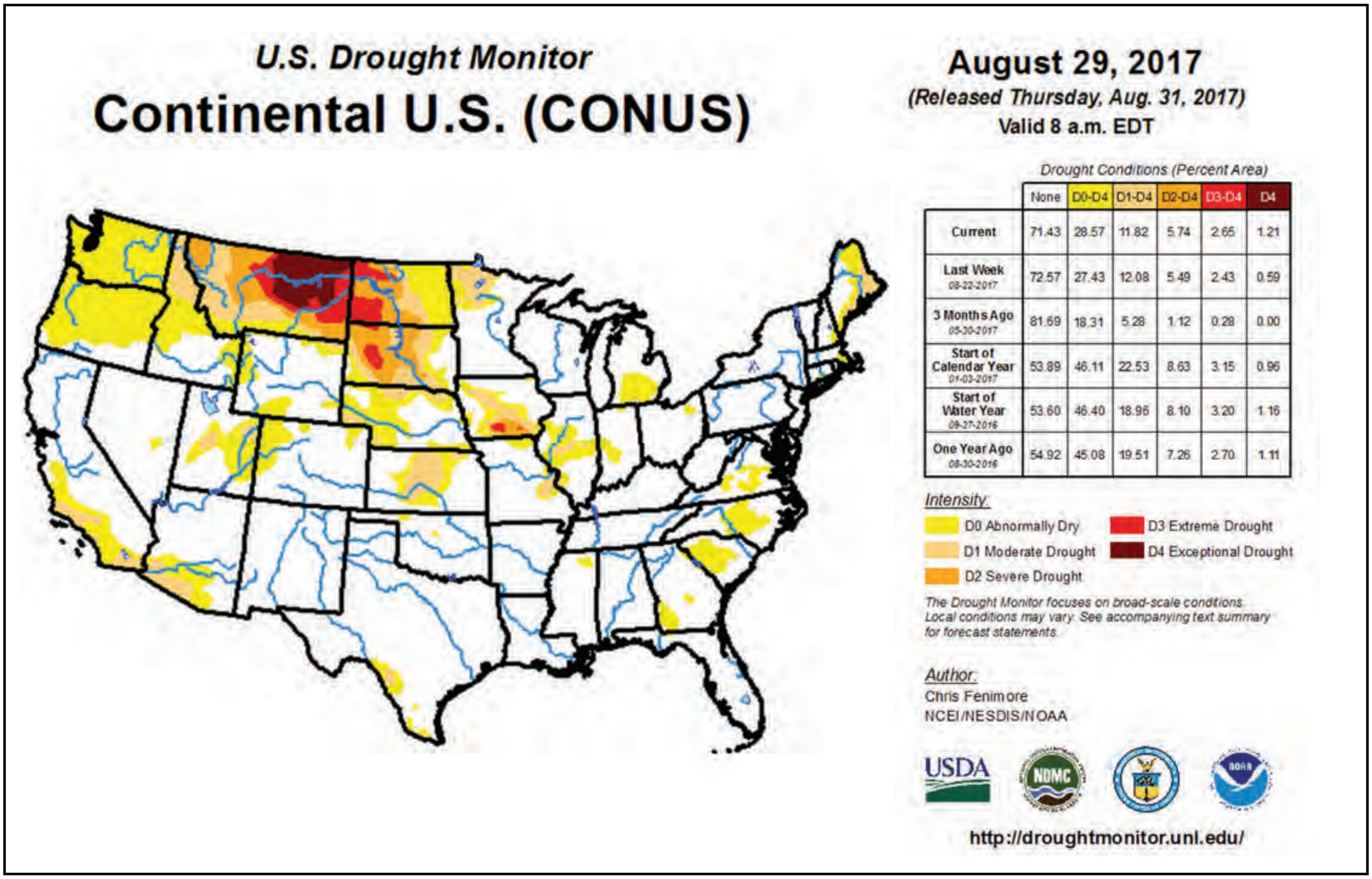
Many plants in YNP are adapted to fire, but probably none more so than the lodgepole pine that dominates the central plateaus. During the last 2,000 years, lodgepole forests in YNP have experienced large (>6,175 acres; >2,500 ha;), stand-replacing fires every 200-400 years (Romme and Despain 1989, Millspaugh et al. 2000). This regular fire cycle, combined with the nutrient-poor volcanic soil inside the caldera, has given the lodgepole an advantage over species that would otherwise be better adapted to the climate (Despain 1990). If fire were to become less frequent, many lodgepole stands would be replaced by spruce and fir. If fire became more common, grassland and sagebrush steppe would gain the advantage.

In recent years, human-caused climate change has increased fire frequency and severity across the western United States, and computer-driven climate models forecast even more rapid and severe increases in the future (Westerling et al. 2006, Westerling et al. 2011, Abatzoglou and Williams 2016, Westerling 2016, Clark et al. 2017). During the period 2003-2012, the northern Rocky Mountains had 889% more fires and 2,699% more acres burned than during the period 1973-1982. Most of these increases were linked to snow melting earlier in the year, which increases drought and the length of the fire season (Westerling 2016). Climate models forecast that by the mid-21st century, the *annual* area burned in YNP will exceed 247,000 acres (100,000 ha); this represents approximately 11% of the total area of the park burned during most years. The climate will be as dry as 1988, the biggest fire year in recent history, every five years or less. If the models are accurate, the time required to burn an area equivalent in size to the entire park will decrease to less than 30 years (Westerling et al. 2006, Westerling et al. 2011).

The recently observed fire increases and the future forecasts are both driven by the strong relationship between drought and fire, but there is some debate over whether fire increases will continue to keep pace with drought increases in the future. Critics point out that drought is only one of the ingredients needed for fire. Fire also needs fuel (forests) to burn; and once a large portion of the forests have been burned, less fuel will be available. The link between drought and fire may weaken, potentially making future fire increases less severe than forecasted by the models (McKenzie and Littell 2017).

Even if the climate model forecasts are overestimating fire potential—making the droughty future seem perhaps twice as fiery as it will in fact be—there is little doubt that YNP's defining greenness will change dramatically in the coming century. There will either be fewer forests or different kinds of forests. If climate continues to be the factor controlling fire, then forests will burn so frequently that lodgepole pine will not have time to reproduce and will be replaced by grasslands, sagebrush, or more fire-resistant Douglas-fir on the central plateaus (Westerling et al. 2011, Clark et al. 2017). If instead fuel becomes the limiting factor, fire activity will decrease only after most of the forests (i.e., fuel) have been burned off. Future fire is also likely to interact with other disturbances that further reduce the size and density of the park's forests. Tree cover will likely decrease in YNP as the "climate envelope"—the combinations of temperature and precipitation that forests require—becomes less common on the landscape (Hansen et al. 2015). At the same time, warming temperatures are likely to increase the frequency and severity of tree-killing beetle outbreaks (Logan et al. 2010, Mitton and Ferrenberg 2012).

As fire danger reaches unprecedentedly high levels in the future, managers will need tools that help them quickly analyze large amounts of data and make high-stakes decisions regarding ecosystem health and human safety. Since fire danger often changes rapidly in a single day and can vary greatly from place to place (figure 1), our responses need to be adaptable and quickly evolving. In this article, I describe a recently-developed, web-based tool that automatically collects data from 15 different weather stations in YNP and presents fire danger in an easy to interpret format. This tool produces results similar to those developed by the authors described above (e.g., Westerling 2006, Westerling et al. 2011);



| | None | D0-D4 | D1-D4 | D2-D4 | D3-D4 | D4 |
|---|---|---|---|---|---|---|
| Current | 71.43 | 28.57 | 11.82 | 5.74 | 2.65 | 1.21 |
| Last Week<br>08-22-2017 | 72.57 | 27.43 | 12.08 | 5.49 | 2.43 | 0.59 |
| 3 Months Ago<br>05-30-2017 | 81.69 | 18.31 | 5.28 | 1.12 | 0.28 | 0.00 |
| Start of Calendar Year<br>01-03-2017 | 53.89 | 46.11 | 22.53 | 8.63 | 3.15 | 0.96 |
| Start of Water Year<br>09-27-2016 | 53.60 | 46.40 | 18.96 | 8.10 | 3.20 | 1.16 |
| One Year Ago<br>08-30-2016 | 54.92 | 45.08 | 19.51 | 7.26 | 2.70 | 1.11 |

*The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. See accompanying text summary for forecast statements.*

*Author:*
Chris Fenimore
NCEI/NESDIS/NOAA

http://droughtmonitor.unl.edu/

**Figure 1. Map depicts drought ratings from the U.S. Drought Monitor (http://droughtmonitor.unl.edu/) for August 29, 2017. Notice YNP was mostly drought free (white on the map) while northern Montana, which was experiencing a severe fire season, had the highest drought rating possible (D4 – dark red).**

however, it has the advantage of being much simpler and less resource-intensive to compute, making it practical as a source of "nowcasts" or present predictions based on data that can be updated near real-time. I also present estimates of mid- to late 21st century fire severity in YNP, which were obtained by applying the web-based tool to future climate data from downscaled general circulation models.

## Nowcasting Today's Fire Danger

The model I developed to nowcast daily fire danger used an "elastic net" linear regression (Zou and Hastle 2005, Bowles 2015). This regression used 83 climate measurements from 15 weather stations to predict the number of acres that would be burned if a fire were left unchallenged. As part of model development, I started with an initial set of 1,150 candidate climate measurements that were then reduced to the 83 "best" predictors. A publication on the development of this model is currently in preparation.

All the climate measurements were taken from snow telemetry stations (SNOTEL; www.wcc.nrcs.usda.gov/snow/) because these stations have few missing values and better quality hydrology parameters than other weather station types. In addition to standard measurements of snow, temperature, and precipitation, I also included calculated parameters such as the Keetch-Byram Drought Index (Keetch and Byram 1968, Alexander 1990) and parameters estimated from a water balance model (Thornthwaite and Mather 1955, Lutz et al. 2010) such as moisture deficit and evapotranspiration.

Once the final regression model was created, it was coded as a module for www.ClimateAnalyzer.org, which delivers climate data summaries and products based on automatically updated, real-time data. An easy way to interpret the model would be as follows: based on 83 predictor variables, I calculate conditions today are as dry as the driest conditions during year X, when Y acres burned. For example, if the elastic net regression determines conditions are nearly as dry as those seen during the height of the fire season in 1988, then the regression will report an estimated fire danger of roughly 800,000 acres (323,749 ha) or 36% of the entire park area. The scale is calculated by the regression on a continuous scale, so any level of fire danger is possible.

## Forecasting Future Fire Danger

In order to forecast fire danger for the mid- and late 21st century, the elastic net regression was applied to future climate data derived from three computer-driven, global climate models (Rupp et al. 2013, Thrasher et al. 2013). The times series extracted from the future models was specific to the same 15 SNOTEL station locations that were used for nowcasting, so that the elastic net regression could be used without changes. For more detail on data sources and methodology, including the estimation of snow parameters in the future data, see Tercek and Rodman (2016).

Fire danger was initially estimated on a daily time-step for the years 2031-2099 and then summarized as 10-year sums (i.e., acres burned per decade). The analysis focused on two climate scenarios or representative concentration pathways (RCPs; Moss et al. 2010). However, here I present only the results for RCP 8.5, which assumes humanity's greenhouse gas emissions will continue to increase at a rate similar to the present.

## Nowcasting Results

Using climate variables (e.g., temperature and precipitation) alone, the final elastic net regression model explained 80% of the variation in annual acres burned in YNP. The regression also correctly predicted the rank of the historical fire years in terms of annual acres burned, i.e., the top five largest fire-years predicted by the model match the actual fire data. In descending order, the top fire years were 1988, 2016, 2003, 2007, and 2002.

During the fire season, fire danger from this algorithm is reported daily, both as a fire danger rating number (ranging from -6 representing least severe to 13 or most severe) and as the number of acres that could be expected to burn if a fire were left unchecked (figure 2). These daily reports are emailed to interested people and also appear on the website at http://www.ClimateAnalyzer.org/y_fire.

The predicted level of fire risk responds very rapidly to both increasing drought and precipitation events. In some cases, it can double or halve in a single day (figure 3). A video showing the daily progression of fire risk during a wet year (1993), a dry year (2016), and the most recent fire year can be viewed at https://youtu.be/vvpXiZ-UjNI.

## Forecasting

Under the RCP 8.5 emissions scenario (figure 4), which is most similar to the currently observed growth in humanity's greenhouse gas emissions, the median model forecast (dashed red line, figure 4) calls for the decades in the mid-21st century to routinely resemble the ten years which ended in 2016, which is historically second only to the 1988 fires in terms of severity. By the end of the 21st century, the median forecast calls for approximately 50% of the park to burn every decade, and the worst forecast calls for roughly 150% of the park burning every decade. The lowest forecast (bottom red line, figure 4) indicates that approximately 3% of the park

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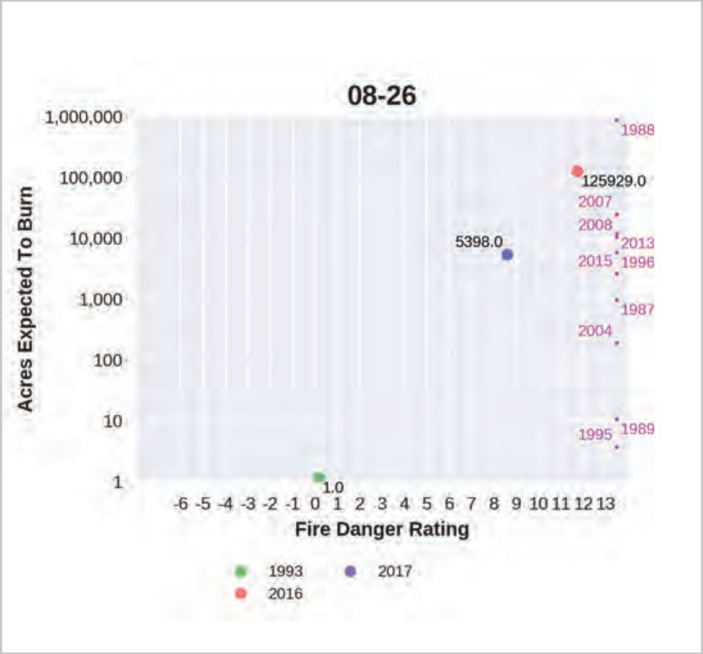

**Figure 2. Daily fire report for August 26, 2017. The expected burn for this day (blue) is 5,398 acres. On the same day in 1993 (green, a wet year), the expected burn was 1 acre. On the same day in 2016 (red, dry year), the expected burn was 125,929 acres. Magenta dots on right of graph show total acres burned during selected years.**

will burn (about 65,000 acres; 26,315 ha,) each decade by the end of the century. These low forecasts were produced when the Centre National de Recherches Météorologiques Coupled Global Climate Model, version 5 (CNRM-CM5) future climate model was used as input for the regression. CNRM-CM5 forecasts that spring snow will persist nearly as late as it does now, producing relatively short fire seasons throughout the 21st century (see Tercek and Rodman 2016 for more discussion).

## Implications

The fire forecasting tool presented here uses a single set of methods to link real-time "nowcasts" of YNP's fire danger to broad-brush forecasts decades in the future. Corroborating other authors (e.g., Romme and Despain 1989, McKenzie and Littell 2017) who found YNP's fire regime to be more climate-limited than fuel-limited, I found that about 80% of the variability in annual acres burned can be explained by drought-related variables derived from a water balance model. The results of this tool, which are much less time consuming and resource-intensive to compute than the complex models cited in the beginning of this article, are now available to fire managers and the public as automatically-generated, daily, fire nowcasts on www.ClimateAnalyzer.org.

How much precision can be ascribed to the nowcasts (figure 2)? In 2017, for example, there were no significant fires in the park, even though the fire predictions called for more than 30,000 acres of expected burn for several days during the end of the season (figure 3). Clearly, the size of the fires that occurs in the real world depends on more than just drought, as measured by the elastic net regression. The 20% of the variability not included in the model does indeed include fuel availability (see above), fire suppression efforts, and other factors such as the presence of lightning when drought conditions are most favorable to start a fire. A fire needs to start in the right place and be left alone long enough to get established before any of the climate factors in my model apply. Even if lightning did strike in a favorable place and time, for example on September 12, 2017, it would not be realistic to expect exactly 35,799 acres to burn (figure 3). No forecasting algorithm is that accurate.

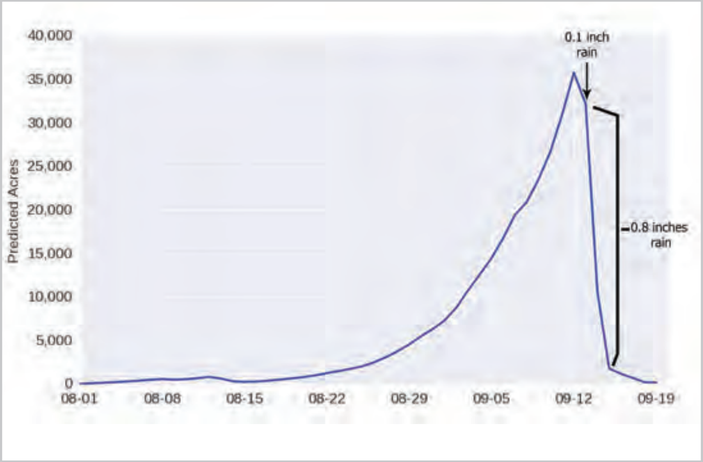

**Figure 3. Daily fire risk predictions for the 2017 fire season. Rain and snow began falling after September 12, which resulted in a rapid reduction in fire risk.**

The best interpretation of the nowcasts would be to focus on powers of 10, i.e., the large scale divisions on the y-axis of figure 2. For example, the green dot in figure 2 indicates the forecast for August 26, 1993, calls for 2 acres to burn, but a more realistic reading would be to say the climate potential indicates less than 10 acres are expected to burn. Similarly, the red dot in figure 2 (August 26, 2016) indicates 100,000 - 1,000,000 are expected to burn, while the blue dot (August 26, 2017) indicates 1,000 - 10,000 acres. I base this "power-of-10" interpretation on the fact that the number of acres reported in the nowcasts (figure 4) are actually the exponentiated (i.e., "un-log-transformed") results of a regression that varies on a logarithmic scale, as well as the realization that a broad power-of-10 interpretation is probably all that matters in a practical, decision-making context. When fire danger reaches the 10,000-1,000,000 acre range, as it did in 2016, pretty much everything burns, including young forests that were newly regenerated from 1988. Fire danger ratings lower in the power-of-10 scales merit proportionately less management concern.

The most likely long-term fire forecasts are the upper two red lines in figure 4. I base this suggestion on two facts. First, the RCP 8.5 results shown here are based on greenhouse gas emission increases that are most similar to those currently observed, while the RCP 4.5 results (not shown in this summary article) are based on the assumption that humanity quickly develops a much smaller carbon footprint (Moss et al. 2010). Second, the lower red line (least burn forecast) is based on a future climate model that assumes most future snow loss in the Yellowstone area will occur in the fall rather than the spring, an assumption that is not validated by historical climate data (Tercek and Rodman 2016).

How should we respond to these long-term fire forecasts? If the upper two forecasts (figure 4) are indeed the most accurate, then the climate during the end of the 21st century will be dry enough to support fires that burn 50%-150% of YNP every decade. One response would be to agree with Schoennegal et al. (2017) and conclude that frequent, large-scale fires are an unstoppable part of our new reality:

> *. . .wildfire policy and management require a new paradigm that hinges on the critical need to adapt to inevitably more fire in the west in the coming decades. Policy and management approaches to wildfire have focused primarily on resisting wildfire through fire suppression and on protecting forests through fuels reduction on federal lands. However, these approaches are inadequate to rectify past management practices or to address a new era of heightened wildfire activity in the west.*

This acceptance might be forced on us for economic reasons. Fighting fires is already very costly, and it is unlikely we will be able to scale up our efforts to meet the forecast increases. During the 2017 fire season, fires in Montana burned roughly 1.2 million acres and cost $1.5 million per day to fight (Smith 2017). Fire-fighting nationwide consumes more than half of the U.S. Forest Service's budget, or approximately $2 billion per year (Worby 2017).

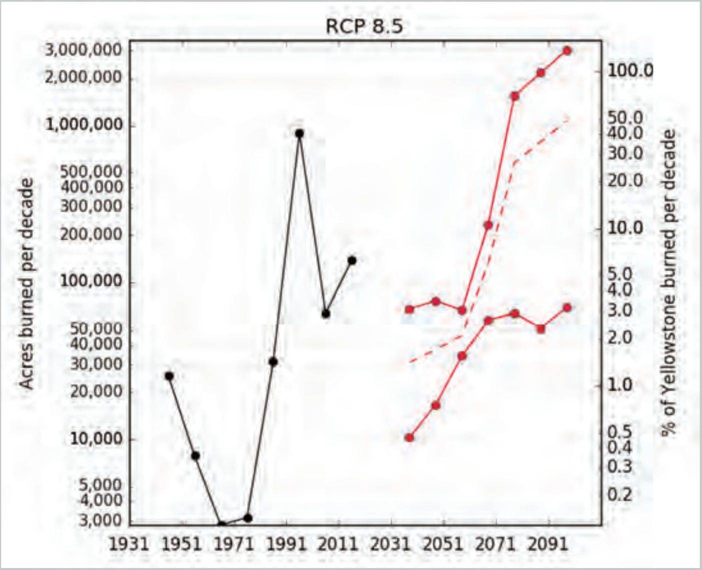

**Figure 4. Historical and forecast fire severity expressed as acres burned per decade. The black line represents actual historical fire observations. The red lines are future forecast fire sizes. Burn forecasts are based on an emissions scenario, which is similar to the current, observed growth in greenhouse gas emissions. The three red lines correspond to the maximum, minimum, and median of the three future datasets that were used as inputs into the elastic net regression. Note the logarithmic scale on the y-axes.**

A second response to the forecast increases in fire would be to make every effort to preserve at least some of YNP's ancient conifer forests to buy time until a better solution is invented (the forests along the Soda Butte Creek drainage are a good example). Some climate scientists and ecologists argue that humanity's greenhouse gas emissions have already exceeded safe levels, and that massive, industrial scale removal of carbon dioxide from our atmosphere is the only hope of avoiding "unacceptable" losses of life, habitat, and infrastructure (Kolbert 2017). If such carbon removal technology is eventually implemented, then efforts expended now to save at least some of YNP's defining greenness will not be in vain. Some people will wish to enjoy the park as we know it for as long as possible; however, if massively-scalable carbon removal technology is in fact invented, we will regret not having saved forests that would be newly viable.

Whichever response is adopted, the tool presented here will be useful. Under either strategy, we can choose to let fires burn more often when conditions are less dangerous. If we accept that massive fires are inevitable and ultimately cannot be prevented, it might still be prudent to eliminate let-burn policies and put out all fire starts immediately when conditions indicate there is an unusually high risk of spread, making it impossible to control the fire's direction. If instead we choose to preserve some old forests, then it might make sense to implement a strategy that incorporates controlled burns in surrounding habitats during times when the tool indicates fire risk is low.

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# Patterns of Primary Production & Ecological Drought in Yellowstone

## *by David P. Thoma, Seth M. Munson, Ann W. Rodman, Roy Renkin, Heidi M. Anderson, & Stefanie D. Wacker*

Photosynthesis converts sunlight into stored energy in millions of leaves, flowers, and seeds that maintain the web of life in Yellowstone. This transformation of energy fixes carbon, supplies organic matter to soils, and creates fuel for wildfire. As the first link of the food chain, new plant biomass is called primary production and provides energy to consumers, including wildlife. While Yellowstone is a mountain environment with deep winter snowpack, the park can get very dry in some years as evidenced by massive wildfires in 1988 and 2016. Droughts like these not only contribute to fire potential, but they affect primary production and the food chain and likely will play an increasingly important role in transforming vegetation structure and composition in the future. Meteorological, agricultural, and hydrological drought have been assessed quantitatively for many years, but key indicators of drought in wildland ecosystems have not been formally defined until recently (Crausbay et al. 2017). One promising new method to do this is by measuring how vegetation responds negatively to drought, and positively to favorable conditions that offset drought impacts. The balance of drought stress and growth has important implications for future vegetation condition as the climate of Yellowstone changes.

Monitoring primary production and predicting future vegetation changes are needed to provide a comprehensive view of park health and anticipate future ecosystem changes (Crabtree et al. 2009, Nemani et al. 2009). Although an important indicator of ecosystem condition, primary production can be time and resource-intensive to monitor in wildland settings using traditional ground-based methods such as clipping and weighing vegetation biomass. Fortunately, ground-based methods can be complemented and enhanced by monitoring primary production with satellite imagery. Measurements of solar radiation reflectance in visible and near infra-red wavelengths can indicate primary production at frequent intervals from the Moderate Resolution Imaging Spectrometer (MODIS) on satellites operated by National Aeronautics and Space Administration (NASA). The Greater Yellowstone Inventory and Monitoring Network (GRYN) staff uses this information to track changes in primary production across Yellowstone over time. They link these measurements to vegetation types, soils, and climate to understand where and when changes in production have occurred and may occur in the future.

## Habitats as Targets for Monitoring

Plants are finely tuned to Yellowstone's climate and soils, and it's these adaptations that enable persistence under stressful conditions. In the absence of disturbance, when all four photosynthetic ingredients (sunshine, carbon dioxide, soil nutrients and water) are abundant, plants grow relatively quickly at their full potential to capture and store energy. However if any of these ingredients are limited, growth slows and can stop entirely if limitations become severe. Plants also adapt to other selective factors including competition, predation, and disturbance such as fire. The response of plant populations to their resources and other growth limitations characterizes the niche where they survive. The resulting assemblage of plants form communities or habitats that support insects, mammals and birds that in turn selectively use these habitats to meet their needs (Garroutte et al. 2016, Phillips et al.). Habitats integrate physical and biological aspects of the environment, occur in repeating patterns, and often form relatively large patches across the landscape that can be monitored by sensors on satellites.

## What Limits Primary Production?

Generally sunshine and carbon dioxide are plentiful in Yellowstone, but there is a prominent pattern of soil nutrients linked to bedrock geology and soil type. Lodgepole pine and associated understory species are adapted to sandy, rocky, and low fertility soils found on the rhyolite plateaus. Subalpine fir, Douglas-fir and Englemann spruce are found on more fertile soils with greater water holding capacity (Rodman et al. 1996). In satellite-based monitoring, we can account for these variations by sampling pixel values from habitat units that have similar soil nutrient and water holding capacity. By accounting for vegetation composition and soil properties, and assuming that sunlight and $CO_2$ are rarely growth limiting factors, we are left with climate and disturbance as the two most important factors that affect primary production in Yellowstone. Disturbances like beetle kill and wildfire in forests are inextricably linked to climate and in some non-forested areas production is also influenced by grazing animals (Frank et al. 2002, Despain 1990).

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Disturbance of any kind affects primary production and is considered an important change agent acting with climate to affect primary production.

## Satellite Monitoring 101

We measured vegetation greenness using the normalized difference vegetation index (NDVI) which is calculated from reflectance in red and near infrared wavelengths measured by the moderate resolution imaging spectroradiometer on the Terra satellite. In each habitat we summed monthly NDVI values across each year from 2000 to 2016 to develop a proxy for annual primary production in each year. We then calculated the annual anomaly or difference above or below average for each year. These fluctuations in annual production were compared against plant water use and plant water need calculated from a water balance model. Evapotranspiration is water used by plants plus a small amount of soil evaporation. Deficit is a measure of drought stress, or unmet water need. By relating primary production to water balance, we calculated two important ecological factors that describe sensitivity to climate and the water balance requirements for different habitats. First, the rate of growth indicates the vegetation sensitivity to evapotranspiration and deficit. It tells us how much primary production changes with variation in water use and need. Second, the average condition in each habitat determines its position along a moisture gradient. We call this a climate pivot point, where vegetation production teeters above and below average (figure 1). Together, sensitivity and pivot points indicate where climate is suitable for each habitat type and what aspects of climate are most likely to cause change at that location. In other words, these factors determine where and when vegetation performs well or experiences stress. Sustained or extreme water balance conditions beyond a pivot point may result in a transition to new vegetation type (Munson 2013).

## What Did We Learn?

We found important differences in sensitivity to water deficit that varied by habitat (figure 2a). In particular, wet meadows and alpine habitats were among the most responsive to water deficit, strongly decreasing in greenness as drought stress increased. Conversely, sagebrush, dry meadow, and wet meadow were the habitats most responsive to evapotranspiration in the positive direction.

Habitats differed in their production potential and were distributed in predictable ways along moisture gradients. That is, dry meadows and sagebrush habitats were located in the driest parts of the park where deficit pivot points were higher indicating they were more drought resistant (figure 2b). These drier habitats also had higher evapotranspiration pivot points, meaning they used more water to maintain above average production. Wet meadows, moist meadows, and moist subalpine fir maintained productivity at lower evapotranspiration values.

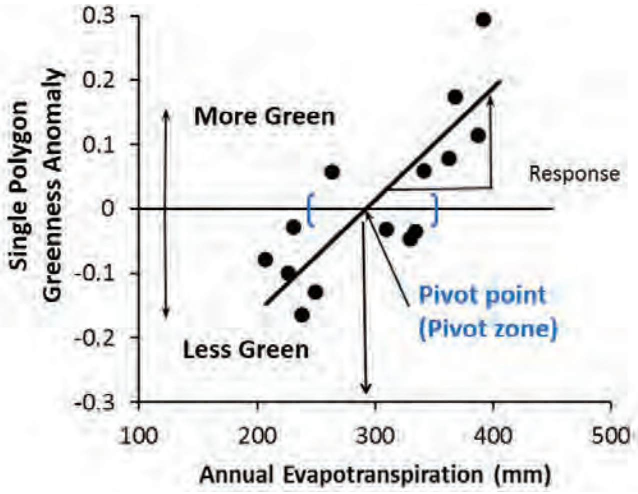

**Figure 1. A water balance pivot point describes the evapotranspiration amount where vegetation production increases or decreases relative to its long-term average condition. The slope of the regression line is the sensitivity or responsiveness of vegetation to changes in evapotranspiration (adapted from Munson 2013). The dots are annual NDVI anomalies coupled with their associated evapotranspiration values for each of 16 years in a single vegetation habitat map unit.**

## Opposites React

Collectively our findings show that wetter habitats respond most strongly to dry years. For example, wet meadows and alpine areas are typically wet during the growing season so they don't respond positively to more water. However, when drought stress increases even a little, they suffer greatly. In other words, they react most strongly to the condition opposite of the condition to which they are adapted. Vegetation accustomed to dry conditions responded positively to wet conditions, but this sensitivity was not as dramatic as the negative response of wet habitats to dry conditions.

## Tradeoffs

Our finding that habitat sensitivity differs along a moisture gradient is explained by a cost-benefit or tradeoff that allows vegetation to survive (Noy-Meir 1973, Munson 2013). Plant traits associated with drought resistance are balanced against the benefits of rapid growth. In dry environments plant adaptations like small leaves and more roots help resist drought, whereas species with larger leaves and more

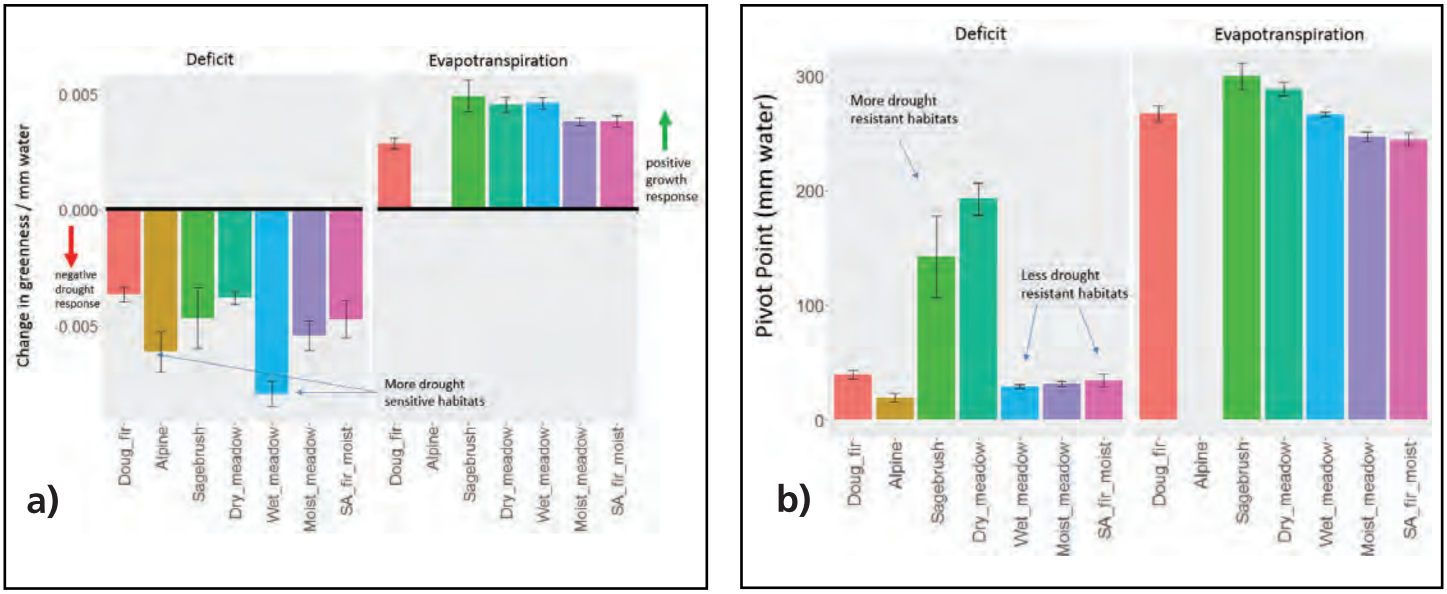

**Figure 2. a) Response of habitat types to deficit, a measure of drought stress and response to evapotranspiration, a measure of water use. b) Deficit and evapotranspiration pivot points indicate the mean climate condition where these habitats occur.**

above ground leaves can't survive. In wet environments leafy vegetation is adapted to grow robustly, which crowds out competitors that grow more slowly. Thus plant traits result in a tradeoff between resistance to drought and strong response to good growing conditions. Generally plant traits are adapted to resist drought or respond strongly to water, which results in differentiation among habitat types and provides an indication of why some habitat types are more sensitive to drought than others. At landscape scales, satellite observations help identify habitats that show sensitivity to drought which may be experiencing stress or warrant attention or additional monitoring to confirm if the cause of change is related to climate, disturbance, or both (figure 3).

## Ecological & Management Relevance

The relevance of these findings lies in our ability to identify where and when habitats may become susceptible to drought and climate change anywhere in the park. This can help determine where and when to look more carefully for evidence of change and perhaps determine ways to mitigate undesirable change. Not all change is undesirable, and not all change will be caused by climate. For instance, areas experiencing an invasion of non-native species like cheatgrass could also experience additional drought induced stress and be high priority areas for management action.

As a practical example, we consider three habitat types that are common in the Tower Junction area that demonstrate how vegetation traits interacting with similar climate may result in very different localized stress responses (figure 4a). On the northern range moist meadows, Douglas-fir and sagebrush habitats are common and experience similar temperature and precipitation patterns. However, the topographic and soil properties where they grow are quite different. Moist meadows occur in fine textured soils, Douglas-fir grow on north aspects, and sagebrush grow in well drained soils on flats or south facing hill sides (Rodman et al. 1996). The interactions between vegetation traits, climate, and site position can result in a different drought stress experience for each habitat (figure 4b). At Tower Junction, annual water deficit has increased by approximately 2.4 inches (60 mm) since 1980. Annual deficit exceeded sagebrush pivot points only two times since 1980, notably in 1988 and 2016, which were so dry they were also extreme wildfire years. However since 1980, annual deficit exceeded the Douglas-fir and moist meadow pivot points 20 and 24 times, respectively. Because vegetation is adapted to handle interannual variation in water availability (within limits) it can recover from drought stress in successive years when growing conditions improve, but persistent stress above deficit pivot points will eventually result in loss of production that includes down-turns in energy and nutrient cycling that will affect animals dependent on these habitats (Garroute et al. 2016). The relationship between positive responses to evapotranspiration and negative responses to deficit during our study indicated a small net positive response in sagebrush and Douglas-fir and a stronger net negative response in moist meadows. This suggests a careful look at species composition and cover in these habitats may be warranted to understand if our observations from space are an early warning indicator of change on the ground.

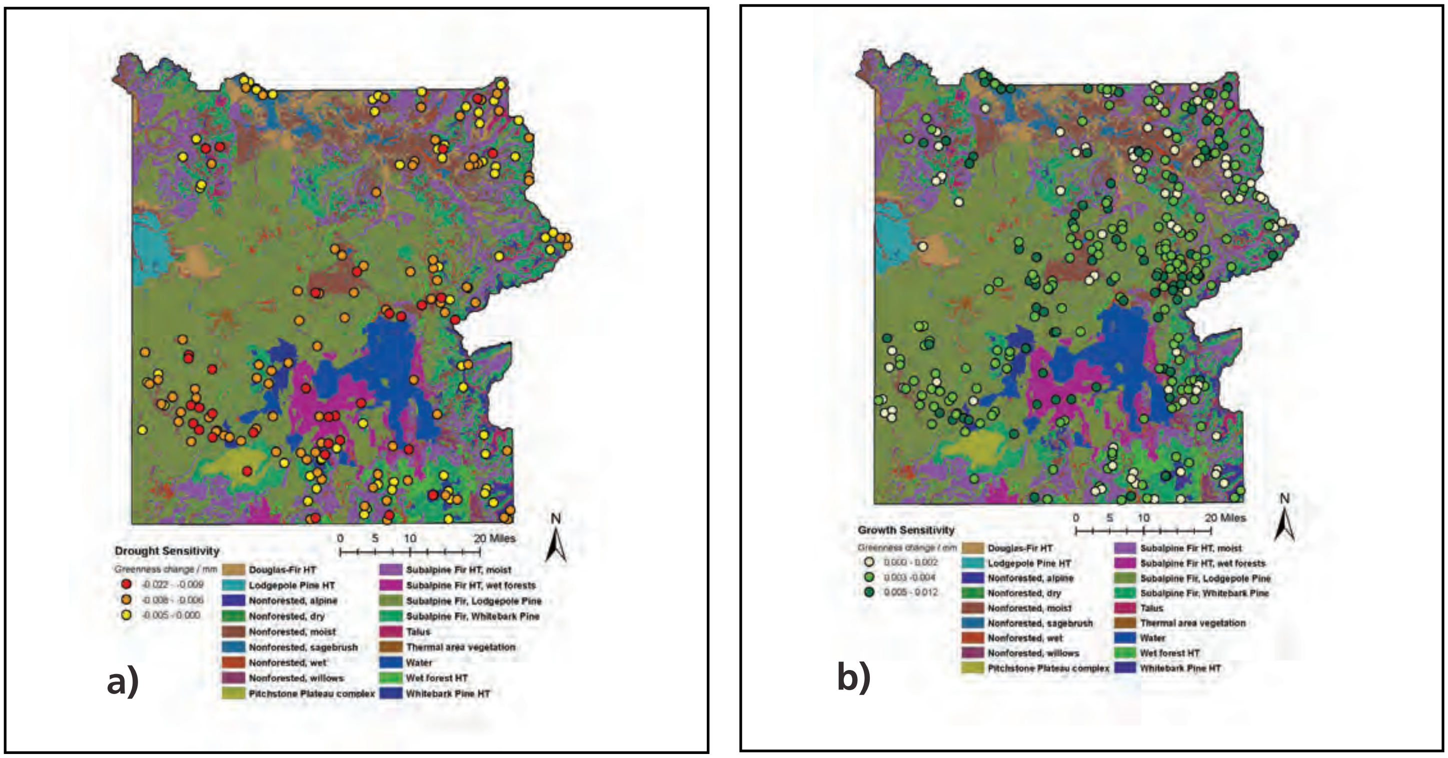

**Figure 3. Habitats marked with a point were sensitive to deficit (a) or evapotranspiration (b). Drought sensitivity was estimated as the change in greenness per millimeter of water deficit. Growth sensitivity was estimated as the change in greenness per millimeter of actual evapotranspiration.**

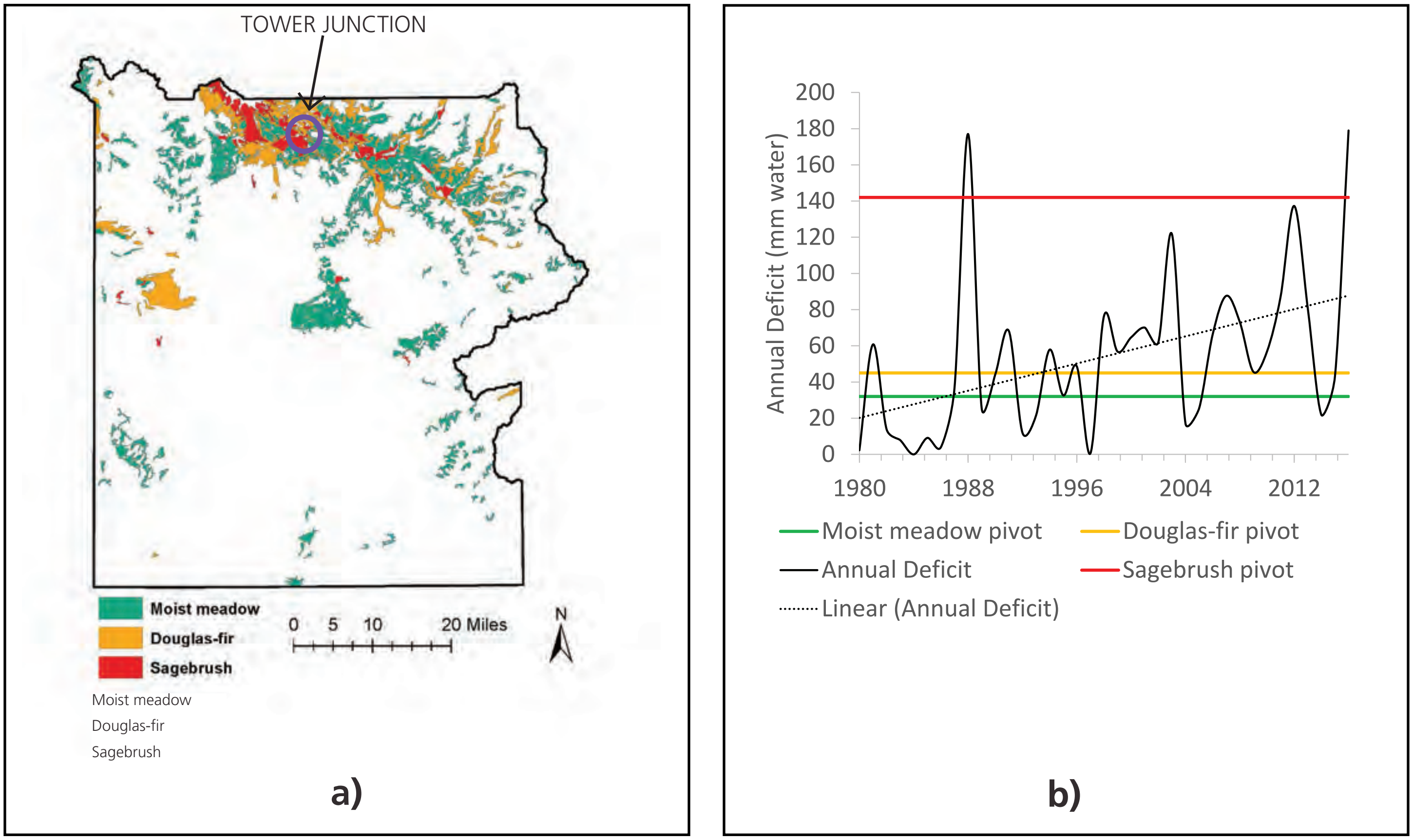

**Figure 4. a) Distribution of three habitats common near Tower Junction, WY. b) Deficit trend at Tower Junction, WY, and pivot points for the habitats shown in 4a. Horizontal lines represent the mean pivot point for each habitat type.**

## Conclusions

The changes expected due to climate change will play out from the plant availability of water and photosynthetic potential in leaves, to landscape-scale primary production. We need to understand how plant and landscape-scale changes are linked by physical and biological processes to understand management options and how to effectively manage inevitable transitions. Our remote sensing approach to understanding drought and recovery provides a window into broad-scale processes that we can't always detect in plot based measurements. Linking these findings to ground-based monitoring programs will provide even greater insight to climate impacts.

The effect of drought can be dampened or amplified depending on plant trait interactions with climate-mediating factors like slope, aspect, and soil water holding capacity. Collectively, these complex interactions determine the severity of ecological drought which, for example, may be more influential in moist meadows than sagebrush habitats on the northern range. Our method demonstrates an efficient means to track drought effects and recovery in important Yellowstone habitats. Tracking the shifting spatial and temporal patterns of drought in wildlands will provide clues to bottom-up processes that shaped the habitats we see today and will continue to have profound effects on plants and animals in the future.

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# Surrogate Species: Piecing Together the Whole Picture

*by Andrea R. Litt & Andrew M. Ray*

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National parks, such as Yellowstone National Park (YNP), are ecologically and socially important resources conservatively valued at $92 billion (Haefele et al. 2016). To properly protect and conserve these places, decision makers require reliable information to track and understand the manifestations of environmental change. However, national parks are large and infinitely complex ecosystems and available financial resources are wholly insufficient to measure and monitor all pieces (i.e., species) and environmental factors that are shaping them. As a result, scientists often select a subset of species and environmental factors (i.e., vital signs) to monitor and characterize ecosystem health ("Vital Sign Monitoring is Good Medicine for Parks," this issue). The idea being that these precious few pieces can provide enough information to see and understand the whole picture. Although physical and chemical characteristics are very instructive vital signs, scientists and decision makers are also interested in monitoring the status of plants and animals in parks. In essence, plants and animals can serve as "sensors" for tracking change, and these biological indicators can offer unique insights into future changes (Whitfield 2001).

Biological indicator species, or **surrogate species**, are species of plants and animals "used to represent other species or aspects of the environment to attain a conservation objective" (Caro 2010). In modern conservation science, using pieces to provide a broader picture of the whole is an increasingly common practice; however, the practice also raises several logical questions: What subset of species provides the most reliable information possible? What species' characteristics should be considered when evaluating potential surrogates? How do we ensure the information gleaned from the monitored subset "speaks" for the rest of the component parts? Although addressing all of these questions is beyond the scope of this article, we will attempt to clarify the types of species' groups considered useful for monitoring environmental change.

There are many types of surrogate species which can be subdivided based on three main conservation objectives. First, some types of surrogate species (e.g., umbrella species, keystone species) can help to identify, designate, or manage areas of high conservation importance and, in doing so, safeguard surrogate species in a manner that provides benefits to countless other species. Second, some types of surrogate species (e.g., flagship or iconic species) can be used to raise public awareness, begin conversations, and secure funding for conservation actions or to support monitoring initiatives. Finally, some types of surrogate species (e.g., indicator, proxy, or sentinel species) can be used as trail markers of environmental change because these species respond predictably to changes or because they reflect the responses of a suite of species. Because of the ever-expanding environmental challenges facing protected areas (Rodhouse et al. 2016), surrogate species that accomplish the last conservation goal are likely most relevant for vital signs monitoring in national parks (see below). However, surrogates that span objective boundaries by also raising awareness of conservation issues and generating support for monitoring can be particularly important to decision makers. What follows are definitions of surrogate species types and examples from YNP for each group. Some of these species are already part of ongoing vital signs monitoring programs or are studied by other researchers, whereas others could be considered as part of an expanded monitoring campaign.

**Umbrella species** are those "whose conservation confers protection to a large number of naturally occurring species" (Roberge and Angelstam 2004, in Caro 2010). These types of surrogates tend to be species that have large home ranges or extensive travel and migratory routes (e.g., elk). The principal assumption being if the large area required by the umbrella species is protected and habitat quality and corridors are maintained, other species also benefit. Often species that require large areas are large bodied, such as grizzly bears, wolverine, and wolves; however, if a species' habitat is patchily distributed, as with butterflies, smaller-bodied animals also may fit the bill. For park managers, maintaining a park or larger collective of protected areas so it provides safeguards for an umbrella species will pay dividends to countless other species of the region that occupy this large protected area. Umbrella species could also be helpful in bolstering public or political support for the protection of areas with exceptional levels of biodiversity, thus promoting connectivity.

**Keystone species** are species that have substantial influence on an ecosystem, to a degree that is disproportionate to their size or abundance. While umbrella species ensure protection of large areas, protecting keystone species ensures parks and ecosystems are diverse and high functioning. Species that greatly modify areas through their activities include beaver, pocket gophers, and prairie dogs. Because of their engineering feats, these species are commonly referred to as **ecosystem engineers**, a type of keystone species. Conservation or restoration of keystone species and ecosystem engineers is often desired in areas where they were previously extirpated. Unfortunately, scientists often don't know a species serves as a keystone or engineer until that species is lost or removed. This latter situation creates challenges in identifying and using these species as surrogates to achieve conservation objectives.


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**Flagship** or **iconic species** are those that can increase awareness and support, engage the public, and raise funding for conservation efforts. Although there are few concrete characteristics of this group of surrogates, these species tend to be described as charismatic or symbolize some unique aspect of the area where they occur. Often these species are large mammals (e.g., grizzly bears, wolves, bison) or birds (e.g., trumpeter swans, loons), but also include pika and other species that are readily recognized as sensitive to a changing climate. These species of conservation concern may also be species listed as threatened or endangered under the Endangered Species Act. Species that are easily recognizable and appreciated by most people are uniquely suited to garner political, public, and financial support, essential for any conservation or monitoring effort. The American pika, for example, is an iconic species that served as the face for multi-year studies (e.g., the NPS I&M Pikas in Peril Project; Wilkening and Ray 2015) focused on the impacts of a warming climate to mountain ecosystems.

Finally, multiple terms are associated with the type of surrogate species that indicate environmental change and ecosystem health, including **sentinel**, **proxy/substitute,**

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and **indicator species** (indicator species hereafter). These species serve as sensors in an early-warning system because they directly reflect environmental change or reflect responses of multiple species. Clearly, indicator species must be sensitive to one or multiple environmental stressors, but they must also convey something about the environmental change or disturbance that is compelling and possibly serving as the justification for management action. Further, indicator species should provide a response in a timely manner. Rapid responses are characteristic of species with short generation times, high reproductive rates, limited mobility, as well as specialized habitat and dietary requirements (e.g., amphibians, butterflies, bats, some plants). Useful indicator species, therefore, are less likely to be able to leave an affected area and less able to switch food resources or habitats when these resources become unavailable. Ideally, these species are also widely distributed, easy to find and identify, and inexpensive to monitor. Scientists may monitor these species by simply documenting presence/absence, collecting more detailed data on population characteristics (e.g., abundance, reproduction), or characterizing the entire community (e.g., how many species are present, which species are most abundant). Scientists often subdivide a taxonomic group (e.g., amphibians, bats, or insects) based on life history traits to identify and monitor just a few species (e.g., one from each sub-group) that might provide the most complete picture about the whole. Since different types of species will respond differently to the same disturbance or environmental change, monitoring several species from multiple, complementary groups can provide a more complete picture and help diagnose problems, prescribe management actions, improve policies, and increase awareness.

Each type of surrogate species outlined above provides unique advantages to a monitoring program and helps to achieve different conservation objectives. As a result, scientists aim to incorporate an amalgam of species as part of a comprehensive vital signs monitoring program. Although some of these types of surrogates are currently included as vital signs (e.g., amphibians) or are measured by other researchers in YNP (e.g., grizzly bears, wolves, bats), additions of other species or taxonomic groups (e.g., insects, aquatic plants, fish pathogens) might be helpful when envisioning a comprehensive monitoring program. Despite our inability to monitor everything due to logistic and financial limitations, carefully considering the most appropriate subset of species can be likened to trying to find at least some pieces in all quadrants of a puzzle to get the best sense of the overall scene depicted. Ideally, the collective suite of diverse monitored species will provide the most comprehensive, early-warning signs to help ecological "doctors" diagnose potential problems and intervene before irreversible damage occurs. Expanding our ecological viewpoint and monitoring out from YNP to the entire Greater Yellowstone Ecosystem or beyond (see Assessing the Ecological Health of the Greater Yellowstone Ecosystem, this issue) could help us to better detect and respond to future environmental changes.

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**Andrew Ray** (see inside cover)

**Andrea Litt** is an Associate Professor in the Ecology Department at Montana State University. Her primary research interests include quantifying responses of animals to human activities and disturbance, exploring the mechanisms of those responses, developing tools for restoration, and informing design of monitoring programs. She holds a BS from the University of Wisconsin, a MS from the University of Florida, and a PhD from the University of Arizona.

# Tribute: Tom Henderson

Tom Henderson, a friend and colleague of Yellowstone National Park, passed away unexpectedly in October 2018. Tom was a devoted husband and father and a Senior Environmental Project Manager with the Montana Department of Environmental Quality's (DEQ) Abandoned Mine Lands Program. Many in Yellowstone worked with and knew Tom for his leadership role in the reclamation and clean-up of the abandoned McLaren Mill and Tailings site on Soda Butte Creek (see "Recovery of Soda Butte Creek, Post-Reclamation," *Yellowstone Science* Issue 26-1).

The abandoned mill and tailings site near Cooke City, Montana contaminated reaches of Soda Butte Creek for nearly eight decades. Until recently, Soda Butte Creek was the only water quality impaired waterbody entering Yellowstone National Park and posed a serious threat to downstream waters and riparian habitats. With the understanding that the constant release of heavy metal-contaminated water from the abandoned mill site was damaging Soda Butte Creek and threatening Yellowstone National Park, Tom literally spent his summers between 2010 and 2014 travelling weekly from Helena to Cooke City to lead the clean-up efforts there. For that, the Yellowstone family is forever grateful.

Tom's personal sacrifice did not go unnoticed and his professional contributions were vital to the success of the clean-up of the abandoned mill and tailings site. Because of the overwhelming success of this clean-up effort, the Montana DEQ was awarded the American Council of Engineering Companies Engineering Excellence Award in 2015. In 2016, the cleanup project earned the first-ever National Association of Abandoned Mine Land Programs award for environmental cleanup. Last year, Tom received a recognition letter from Yellowstone Superintendent Dan Wenk for his leadership role and extraordinary achievement associated with the cleanup on Soda Butte Creek. And Tom was just awarded the 2019 Montana Watershed Coordination Council's Watershed Stewardship Award for his influential work on Soda Butte Creek and around Montana.

Tom's work will forever be remembered as a catalyst for the ecological recovery of Soda Butte Creek. His efforts not only led to improvements in water quality, but Tom helped develop and execute a monitoring strategy that was used to formally quantify these improvements and measure the response of key biological indicators following the cleanup. Collectively, these efforts and the resulting data led to a determination by the Montana DEQ that metals in Soda Butte Creek now meet water quality standards. Soda Butte Creek has been removed from Montana's Impaired Waters List. For the Montana DEQ and its project partners, this marks the first time in Montana history that a water body has been removed from the Impaired Waters List following the successful implementation of abandoned mine cleanup. More importantly, Tom's work facilitated the establishment of a Yellowstone cutthroat trout stronghold in Soda Butte Creek.

Tom Henderson was a recognized leader in his field and an inspiration to those who knew him as a friend and colleague. Tom was keenly and ever-focused on the BIG picture and had the ability to sort through details and focus beyond the boundaries of the projects he managed. For those that knew Tom well, he was much more than a world class hydrogeologist. He was best known for his great loves—his family, music, educating others, and spending time in the mountains. Tom was an inspiration to all who knew him and he enjoyed his work and loved life to the fullest—he worked hard, laughed hard, and travelled regularly. Although he enjoyed spending time in the mountains around Yellowstone's Northeast Entrance, the stories he shared around the campfire or wood stove were those of his backcountry excursions with family. From the Bitterroots to the Dolomites, Tom was always preparing for the next experience with his beloved family.

Tom will be sorely missed by his National Park Service friends and colleagues, but his wonderful legacy will live on through his great work and passion for collaboration. To those readers who have not yet seen the restoration of the McLaren Mill and Tailings site (the fruits of Tom's labor) just outside Cooke City, Montana, please consider stopping by during your next visit. The project was an overwhelming success and serves as a reminder of how one person can make a difference. Tom, through his clean-up work on Soda Butte Creek, single-handedly made Yellowstone National Park a better place.

*– Andrew Ray*

**Right: Tom Henderson evaluating Soda Butte Creek channel conditions in August of 2018, four years after the reclamation and clean-up of an adanboned mill near Cooke City, Montana. NPS Photo - A. Ray**

# SHORTS

## Yellowstone's Birds Are Vital

### *by Robert H. Diehl & Douglas W. Smith*

Traveling through Yellowstone National Park (YNP), visitors frequently stop to enjoy the park's birds: small songbirds flitting about the willows, sandhill cranes engaged in their ritual mating dances, or myriad species of waterfowl loafing in one of the park's many wetlands. Typically while driving the roads of YNP, a majority of visitors consider a stopped car and raised binoculars a sure sign of some large mammal sighting. Bird watchers in YNP are familiar with this expectation and steel themselves to deliver the tough news. Certainly the park boasts its share of large charismatic birds, including trumpeter swans and bald and golden eagles; however, next to the bison, wolves, bears, and elk that bring so many visitors to Yellowstone, the park's birds often seem overlooked. Regardless, YNP is home to considerable bird diversity. Over 300 species have been documented in the park (McEneaney 2006), and each brings unique habits and behaviors that contribute tangibly to the park's character and function as a healthy ecosystem.

YNP, like most large geographic areas that vary considerably in elevation, encompasses a variety of habitat types that sustains many bird species, but not all habitats support similar levels of avian diversity. Although spruce-fir forests, certain river corridors, and scattered wetland areas represent a small proportion of the total park area, they often contain rich plant communities that disproportionately concentrate bird life. With a shrinking winter snowpack ("The Spatial Footprint and Frequency of Historic Snow Droughts in Yellowstone," this issue) and higher-frequency fire regime ("Nowcasting and Forecasting Fire Severity in Yellowstone," this issue) becoming characteristic of a future Yellowstone that is warmer and drier, spruce-fir forest regeneration may be compromised (Stephens et al. 2013) and wetlands will dry or become more ephemeral (Schook and Cooper 2014) resulting in shifting bird communities and a likely reduction of avian diversity. Park scientists and resource managers are challenged to identify ecological measures, or vital signs, best suited to indicate current and future health of these and other habitats within the park. The most useful vital signs are easy to measure, influence large portions of the ecosystem, and may be biological or non-biological in nature (YCR 2018).

**Magpies, ravens, and a wolf scavenging a carcass.** NPS PHOTO - J. PEACO

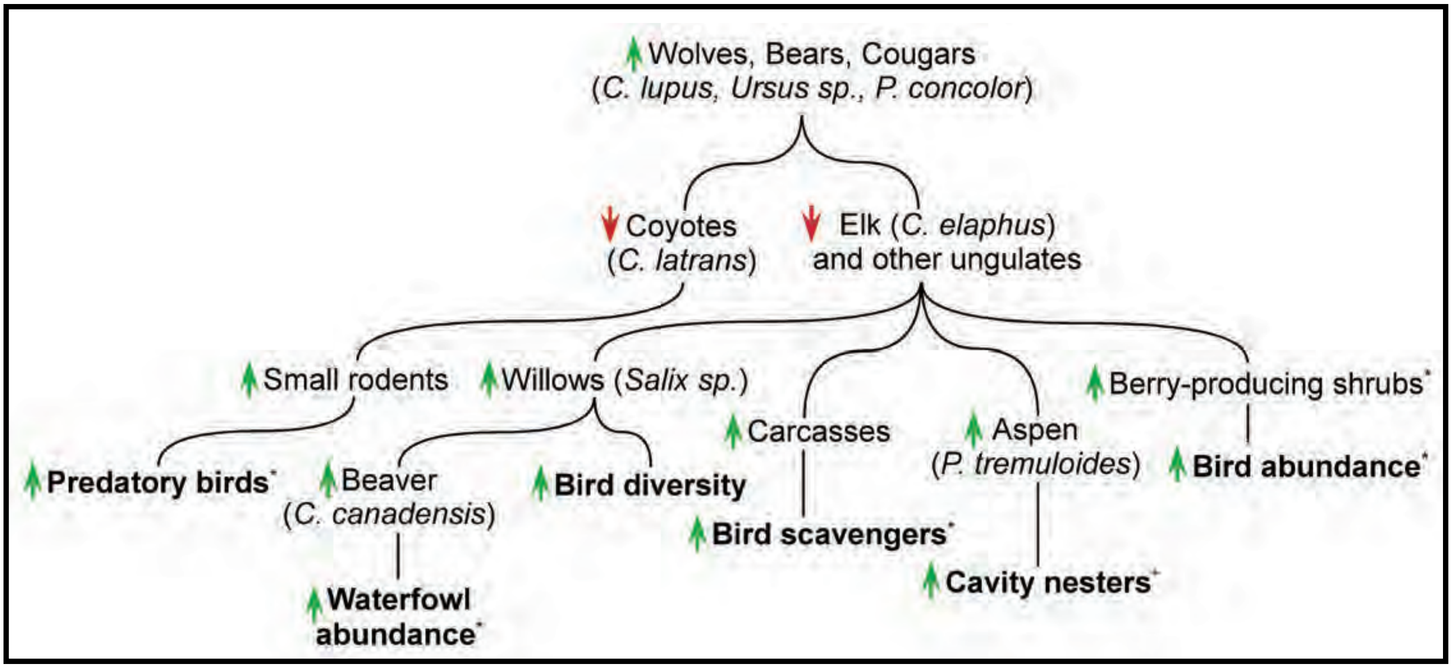

**Figure 1. How organisms influence each other's abundance or presence and absence in a given habitat is extremely complex. This highly simplified diagram captures some of the dynamics that can affect bird numbers and distributions. Specifically, the restored top predator community may influence ungulate and coyote numbers or alter their distributions in ways that ultimately influence the abundance and distribution of birds (developed from Ripple and Beschta 2012 and cited research therein; * indicates relationships that are speculative but theoretically sound). Upward green arrows indicate an increase in abundance, and downward red arrows indicate a decrease.**

In certain circumstances, bird behavior or population status may play the role of a vital sign by indicating subtle yet important changes in habitat quality that might otherwise defy easy measurement and detection. Unlike most other park fauna, birds cover a lot of ground, making them efficient at tracking environmental change (Tingley et al. 2009) and, therefore, responding by occupying habitats that best suit their needs for food, cover, and nesting locations. In this way the presence or absence of certain birds may serve as a vital sign on the health of local habitats. For example, birds that seasonally move to higher altitudes to breed, so-called altitudinal migrants, tend to be flexible in the timing of their movements and the habitats they occupy (Boyle 2017). Tracking these changes in the timing of migration and the locations of breeding and wintering areas of certain birds may serve as an early and tangible signal of habitat change that may take longer to become apparent by other means.

Rather than serve as vital signs themselves, bird populations more often are the beneficiaries of other more fundamental vital signs such as water quality or the status of some more influential species further up the food chain. Ideal vital signs for birds directly or indirectly indicate the health of bird populations through their influence on key aspects of their biology (e.g., reproduction or foraging). For example, chemical screening of soil, water, or biological samples can detect a variety of potential pollutants or toxins before they reach critical levels that may be harmful to populations. Mercury concentrations discovered in fish samples taken from several lakes within the park exceeded toxicity levels that might be harmful to fish-eating birds (Smith et al. 2016). Alternatively, the status of populations of certain so-called keystone species can serve as a vital sign for the overall health of ecosystems. As their namesake implies, keystone species, often top predators, have disproportionate influence over the character of their ecosystems. Their control of large mammalian prey populations cascades down through the food chain to influence the populations of innumerable species of plants, small mammals, and birds. For example, wolves acting through their influence on ungulates and other prey may indirectly impact the populations of numerous bird species (figure 1).

YNP's birds, through their diversity and rich repertoire of behaviors, perform numerous ecosystem functions throughout the park. Woodpeckers excavate cavities used by other birds and mammals; nutcrackers and other seed-eating birds promote plant reproduction by dispersing seeds; scavenging birds including vultures, ravens, and eagles consume carrion; and large numbers of insect-eating swallows, flycatchers, warblers, and thrushes spend their breeding seasons converting mosquitos into baby birds.

NPS PHOTO - J. FRANK

YNP staff conduct numerous surveys each year to monitor park birds. When birds represent essential vital signs, such monitoring helps ensure the health of other plant and animal populations and the unique roles they fill in many habitats.

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# Yellowstone Bats: An Important Indicator of Ecosystem Health

## *by John J. Treanor, Joseph S. Johnson, Eli H. Lee, & Austin G. Waag*

**A Townsend's big-eared bat (*Corynorhinus townsendii*) captured during a mist net survey in Yellowstone National Park.**

The popularity of Yellowstone National Park (YNP) is often gauged by the abundance of wildlife that calls it home, but the ecological health of the park is regularly assessed by a suite of indicator species. Bioindicators are typically species or species groups that are easily observed; however, a silent gray blur darting overhead at twilight may turn out to be an important indicator of environmental health. Despite their secretive nature, bats are believed to be excellent ecological indicators because they are sensitive to human-induced changes in climate and habitat quality (Jones et al. 2009). Bats are a diverse taxonomic group and their small size, high mobility, and wide distribution allow them to respond to disturbance in measurable ways. Thus, the long-term monitoring of bats may provide important insight into the ways in which biological communities are changing over time.

Currently, bat populations in North America are facing significant threats from climate change and the emerging infectious disease white-nose syndrome (WNS). Climate change is likely to influence wildfire regimes in the Greater Yellowstone Area (Westering et al. 2011). For bats in YNP, an increase in fire frequency could limit the availability of daytime roosts, often large dead trees, needed for reproduction by some species. Additionally, WNS continues to spread across North America, and the fungus that causes WNS was recently confirmed in bats from South Dakota and Wyoming. Cave hibernating bats in the eastern U.S. have declined by more than 90%, leading to worries of regional extirpations and extinctions (Frick et al. 2010). Most of the 13 bat species in YNP are expected to be susceptible to WNS and are poorly suited for recovery from substantial population declines because most species rear only a single pup per female each year. These impending threats from climate change and WNS highlight the need for a comprehensive, long-term monitoring program using innovative methods. Here we describe the components of YNP's bat monitoring program and how these efforts are building the baseline data needed to identify impacts to bats over time.

## Acoustic Survey and Mist Net Capture

Acoustic survey and mist net capture are the primary methods used to monitor bats in YNP. Acoustic monitoring is a noninvasive sampling technique that provides important information on the distribution of bat species and their activity over a large spatial area and across seasons. In YNP, acoustic sampling includes stationary point surveys and mobile transect methods. Point surveys allow researchers to deploy recording devices in remote areas of the park that log the echolocation calls of bats for extended periods of time without an observer present. This approach has been used to identify species that winter within the park and document bat activity across the summer. The western small-footed myotis is the species recorded most frequently during winter, while the little brown myotis is the most commonly recorded species during summer.

A shortcoming of acoustic data collected from the point surveys is that the level of bat activity does not necessarily correlate with abundance or density of bats because the automated detectors will continuously record multiple passes of individual bats. To address this limitation, mobile transects, which involve recording bats while traveling along road segments (15-30 miles; 25-48 km), have been used to estimate relative abundance of bats across the landscape. The recorded bat passes are assumed to represent an individual bat because the survey vehicle is traveling slightly faster than the maximum speed of most bats (Roche et al. 2011). In YNP, mobile transect surveys are used to track bat activity from spring to autumn (figure 1), which corresponds with migration and hibernation behaviors. Peak bat activity occurs in June and July, with approximately 26 calls recorded per hour of sampling. March and April have the lowest average number of detections with less than two calls per hour. The little brown myotis was the most commonly detected species with 38% of the recorded calls. Acoustic data is providing information on species-specific activity parkwide.

While acoustic sampling provides valuable data, some information can only be collected through direct observation of a bat in hand. For example, sex, age class, and reproductive status are determined only after capturing bats with mist nets. Mist net surveys can also identify the time of year when juvenile bats are becoming volant (i.e., able to fly), which, if delayed, may indicate habitat conditions have changed and pregnant females are struggling to find prey. Thus, a robust mist-netting program not only provides information on the bats captured, but also provides insight into the productivity of populations and the quality of their habitat.

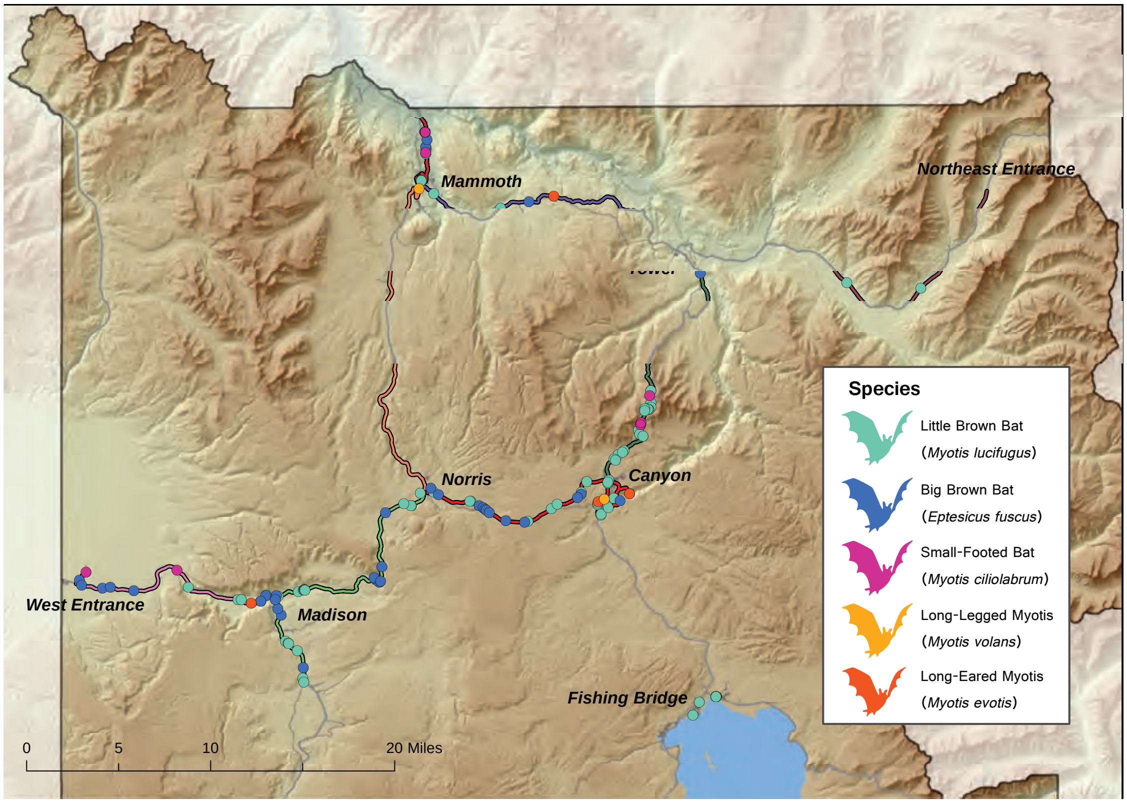

**Figure 1. Locations of mobile acoustic surveys on park roads. These surveys provide species' occurrence data over a large spatial area. Here we have only plotted the more common bat species that may be susceptible to white-nose syndrome. Surveys were not conducted between Mammoth and Norris because the road section was closed for repair.**

## Bat Migration and Roost Monitoring

For bats in YNP, the timing of hibernation and seasonal migrations are important responses to changing environmental conditions. Both events offer clues on how bats survive and reproduce in a region with severe winters and brief growing seasons. In the months following emergence from hibernation, female bats must devote enough energy to gestation and lactation to wean their young early enough to allow both mother and young time to accumulate critical winter fat reserves (Kunz et al. 1998). Yellowstone summers may put an energetic and time constraint on this process. Acoustic monitoring and radio-telemetry methods were used to document the timing of spring and autumn migration and to determine whether bats overwinter in YNP (Johnson et al. 2017). We detected acoustic activity of bats throughout the winter and were able to radio-track several species through late October—long past the cold-induced decline of insect prey. Bat activity dramatically increased between March and April, which is notable because daily minimum temperatures averaged less than 32°F (0°C) and may represent an adaptation to Yellowstone's short summers.

For decades, bat monitoring included counting bats as they emerged from their daytime roosts. However, these emergence counts do not provide accurate estimates of the population using a particular roost. A novel approach to roost monitoring has been implemented in YNP using a radio-frequency identification (RFID) system. This technology is used to continuously monitor the population status of bats occupying individual attic roosts. The RFID monitoring system is recording bats (individually marked with tags) in three buildings spanning 24 miles (39 km) of YNP's northern range. From 2015 to 2018, 301 female little brown bats were RFID-tagged providing nearly three million detections that included approximately 60% of the tagged bats. The implanted tags do not require batteries and are expected to operate for the lifetime of the little brown myotis, which may be over 30 years (Fenton and Barclay 1980). The monitoring system provides information on the fidelity of tagged individuals to specific buildings. The monitoring system also detects seasonal arrivals and departures from summer roosts, improving our understanding of bat migrations. Data from marked bats will allow biologists to track the survival of individuals and to monitor the productivity of bat colonies.

Long-term monitoring of biological indicator species, like bats, can be challenging and often requires substantial financial commitments. However, the importance of these types of programs cannot be overstated. Development of effective monitoring strategies can provide important insight into the ways in which biological communities change in response to climate change, habitat deterioration, and emerging infectious disease.

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**John Treanor** is a Wildlife Biologist for the National Park Service working in the Yellowstone Center for Resources. He oversees the wildlife health laboratory and manages the Yellowstone wildlife health program, which addresses disease and health concerns in park wildlife. John has worked in Yellowstone since 2001 and currently supervises projects involving amphibians, rodents, bats, and ungulates in the park.

# Taking the Pulse of Wetlands: What Are We Learning From the Amphibian Vital Sign?

### *by Andrew M. Ray, Debra A. Patla, & Charles R. Peterson*

The air is thrumming with trills as our field crew in-training scans with binoculars, searching for a tiny head hidden in the roadside marsh. A voice from a car window calls out, “Do you see a bear?” “No, frogs!” we joyfully exclaim. But the baffled tourists depart before we can explain.

Why indeed care about tiny frogs, with so many spectacular and elsewhere-rare animals inhabiting Yellowstone National Park (YNP)?

Amphibians were selected as one of 12 vital signs for the Greater Yellowstone Network in 2005 (“Understanding Dynamic Ecosystems: The Pursuit of the Greater Yellowstone Network,” this issue). In light of global amphibian declines, there were urgent concerns about greater Yellowstone’s amphibian populations. Are native amphibians declining in Yellowstone and Grand Teton national parks; and if so, what are the causes? Furthermore, could amphibians inform us about changing conditions in wetlands, one of the most vital resources of the greater Yellowstone region?

Determining how to monitor these small animals across the large landscape was a challenge that engaged scientists from multiple organizations. Since 2006, we have followed a detailed protocol to annually monitor four native amphibian species at about 300 wetland sites in 30 watershed units (catchments) distributed across Yellowstone and Grand Teton national parks. Through our monitoring we have determined the western tiger salamander, boreal chorus frog, and Columbia spotted frog are widespread. Western toads are less widespread and thought to be less common than they were historically (Koch and Peterson 1995).

This program, now in its 14th year, covers a larger geographic area and more years than any other amphibian monitoring effort in the region. The rich data set garnered from extensive field work is yielding important insights about relative abundance, geographical distribution, and trends of the four most widespread amphibian species (Hossack et al. 2015, Ray et al. 2016). We are learning how amphibians indicate the importance of specific aspects of wetlands such as beavers, introduced fish, water depth, and spatial patterns (e.g., clustered or isolated water bodies). Analysis of the data

**Male boreal chorus frog inflating throat sac to call at a breeding site. Male chorus frogs, only 1 inch (2.5 cm) long at maturity, are by far the loudest amphibian in Yellowstone.** (PHOTO - ©S. CORN)

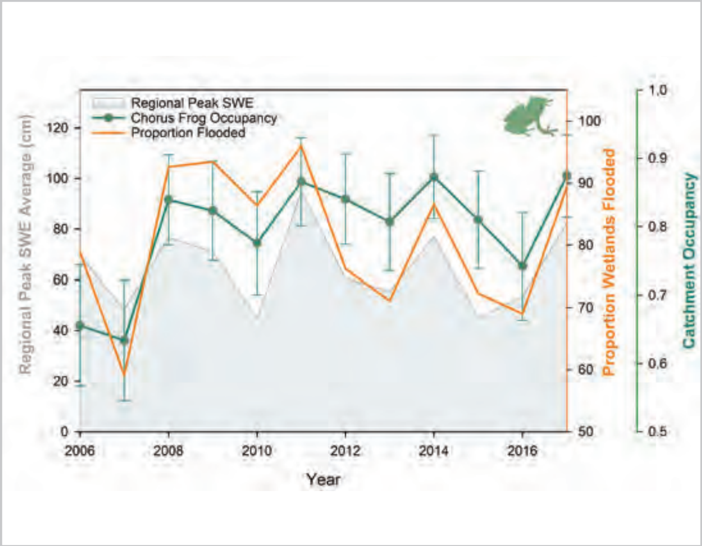

**Figure 1. Apparent is the general relationship between regional snowpacks (estimated as Snow Water Equivalent; SWE shown as grayed area), the proportion of wetlands that contain water (i.e., proportion wetlands flooded; orange line), and and the proportion of monitored areas with chorus frog breeding (catchment occupancy; green line).**

is ongoing and we expect expanded understanding in the coming years.

The boreal chorus frog (photo) has emerged as an outstanding indicator of wetland conditions with respect to climate. More so than YNP's other amphibian species, chorus frogs reproduce in very shallow, seasonal wetlands that are most subject to annual weather-mediated changes. Such wetlands are dynamic and variously abundant or scarcer according to each year's weather. Across all the catchments, we have found a strong, positive relationship between chorus frog breeding occurrence, snowpack moisture (peak snow water equivalent; SWE), and the availability of wetlands (figure 1). Conversely, lower SWE corresponded to fewer wetlands available for breeding and, therefore, a reduction in chorus frog breeding.

If wetlands are of interest, why not just measure wetlands rather than frogs? It is because wetlands, depending on their permanency or resistance to drying, are made up of unique mixes of plants and animals (Ryan et al. 2014). Shallow, seasonal wetlands filled by melting snow are the first to dry in years with reduced snowpacks. These wetlands typically contain rapidly developing species like fairy shrimp, midges, and boreal chorus frogs. During years with low snowpacks when shallow wetlands dry early, there are fewer wetland sites available for breeding boreal chorus frogs. Conversely, the number of breeding sites increases sharply in abundantly wet years, such as 2011, 2014, and 2017. Through years of monitoring, this relationship between boreal chorus frogs and snowpacks has become obvious (figure 1; Ray et al. 2016). The establishment of warmer, drier weather patterns would have consequences for snowpacks, wetlands, and boreal chorus frogs, profoundly changing YNP's spring and early summer soundscape. While the ecological effects of changes in amphibian populations are difficult to fully anticipate, we know amphibians are just one of many species dependent on these seasonal habitats (Ryan et al. 2014). In wetland food webs, amphibians are both prey and predators, and they occupy a unique niche as the only vertebrate with an aquatic larval (e.g., tadpole) stage and terrestrial adults. Garter snakes and other predators may be so strongly linked to amphibians that their presence in wetlands is entirely dependent on them (Matthews et al. 2002). In Yellowstone and Grand Teton national parks, the boreal chorus frog is our "spokesfrog" for seasonal wetlands and their vibrant biological diversity.

Will people of the future have the opportunity to enjoy frogs singing their role in the great animal orchestra of YNP? We plan to continue documenting how amphibians are faring, to help us better understand and predict the effects of changing climatic and wetland conditions. Your encounters with amphibians can help the monitoring effort: please see the iNaturalist box to learn how to share your observations. And remember, amphibians are sensitive species. Please treat them with respect and do not harass or pick up amphibians while you are naturalizing.

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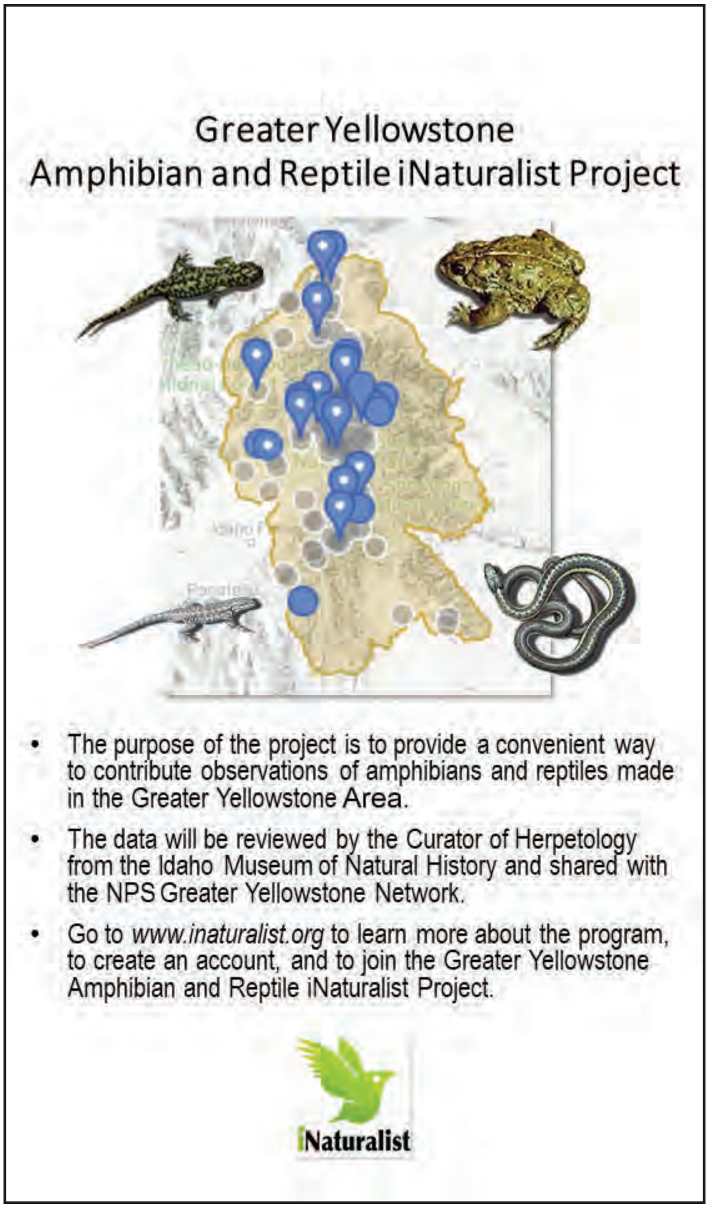

Greater Yellowstone
Amphibian and Reptile iNaturalist Project

- The purpose of the project is to provide a convenient way to contribute observations of amphibians and reptiles made in the Greater Yellowstone Area.
- The data will be reviewed by the Curator of Herpetology from the Idaho Museum of Natural History and shared with the NPS Greater Yellowstone Network.
- Go to *www.inaturalist.org* to learn more about the program, to create an account, and to join the Greater Yellowstone Amphibian and Reptile iNaturalist Project.

iNaturalist

**Andrew Ray*** (see page inside cover)

**Debra Patla*** (top left) has been engaged with the design and implementation of the cooperative amphibian monitoring program in Yellowstone since its earliest days (2000). Her work with amphibians began in 1993 with MS research (Idaho State University) investigating the decline of a Columbia spotted frog population near Lake Lodge in Yellowstone, and other amphibian projects across the Greater Yellowstone Ecosystem. She is a Research Associate of the Northern Rockies Conservation Cooperative.

**Charles Peterson*** (bottom left) is a Professor of Zoology in the Department of Biological Sciences at Idaho State University. He has been studying the amphibians and reptiles of Yellowstone National Park since 1989 and helped develop the amphibian monitoring program.

**All authors contributed equally to this article.*

# The Yellowstone River Fish-Kill: Fish Health Informs and Is Informed by Vital Signs Monitoring

## *by Patrick R. Hutchins, Adam J. Sepulveda, Lacey R. Hopper, & Ken D. Staigmiller*

Trout are socioeconomically and ecologically important in the Greater Yellowstone Area (GYA), yet these fish face numerous threats. Disease may begin to play a larger role in reducing fish populations, partly because many existing threats may interact to exacerbate the frequency, extent, and severity of fish diseases (Lafferty 2009). For example, habitat loss and low summer flows might interact to stress fish, making them more susceptible to disease while also increasing fish densities in microhabitats, thereby creating conditions where infectious diseases are more easily spread. Conservation and management efforts to mitigate these threats often involve reactionary measures to unforeseen events. Long-term monitoring of aquatic vital signs and fish health, however, may provide important insights for predicting the spread of fish diseases and the extent and severity of outbreaks.

A need for monitoring the health of wild fish populations was first recognized in 1996 after the causative agent for whirling disease, *Myxobolus cerebralis*, was identified in Montana's Madison River. This parasite decimated wild trout populations and prompted the U.S. Fish and Wildlife Service (USFWS) to request funding for the National Wild Fish Health Survey (NWFHS), which aims to detect known pathogens and to discover new or emerging pathogens that may threaten fish populations. With changing environmental conditions and high potential for movements of pathogens from endemic to naive waters, continuous monitoring of wild fish health may be a necessary component of a comprehensive vital sign monitoring campaign.

The 2016 mass mortality event in the Yellowstone River highlighted the complexities of fish disease. Between mid-August and mid-September thousands of dead mountain whitefish (*Prosopium williamsoni*) were documented between Emigrant and Springdale, Montana (Opitz and Rhoten 2017). In response to the event, Montana Fish, Wildlife and Parks (FWP) closed 183 miles (295 km) of the Yellowstone River and all tributaries to all recreational activities. The USFWS's Bozeman Fish Health Center identified Proliferative Kidney Disease (PKD) as the cause of the mortalities. PKD is characterized by anemia and severe inflammation of the kidney (Hedrick et al. 1993). Clinical signs usually only develop when water temperatures exceed 59°F (15°C) for several weeks or longer (Ferguson 1981).

While its presence had been reported in Montana, the causative agent of PKD in salmonid fish, *Tetracapusloides bryosalmonae*, was not known to be present in the Yellowstone

**Dead Mountain whitefish (*Prosopium williamsoni*) found along the Yellowstone River shore near Mallard's Rest fish access and south of Livingston, Montana in August 2016.**

River. This raised concern of a recent introduction of the parasite to the Yellowstone River and wrought fear of its spread upstream towards Yellowstone National Park. In the wake of this outbreak, many questions loom, including: How long has the parasite been in the Yellowstone River? Are extreme environmental conditions to blame for the 2016 PKD outbreak? Why were no outbreaks of that magnitude observed in neighboring water bodies known to harbor the parasite? Are mountain whitefish, in particular, more susceptible to the disease than trout?

## What We Have Learned Since the 2016 PKD Fish Kill

To learn about PKD and *T. bryosalmonae*, the U.S. Geological Survey's (USGS) Northern Rocky Mountain Science Center has partnered with the USFWS Fish Health Center and Montana FWP to develop new molecular tools for *T. bryosalmonae* surveillance and to use these tools to describe the occurrence and distribution of *T. bryosalmonae* in rivers in the GYA and western Montana. In winter 2017, this collaborative effort developed enhanced molecular tools for screening water and fish tissue samples for presence of *T. bryosalmonae* DNA (Hutchins et al. 2017, 2018). These tools were then used to screen tissue samples collected from apparently healthy trout and whitefish in Montana rivers in 2016 and 2017, as well as archived fish kidneys preserved in 2012 from the Yellowstone River (figure 1). Presence of the parasite in a water sample or in fish tissue is not indicative of diseased fish or fish mortality and our findings likely do not represent the full extent of *T. bryosalmonae*'s distribution in the GYA or the Intermountain West. We did, however, document *T. bryosalmonae* DNA in nearly all waters where fish were sampled, including multiple rivers in the GYA (figure 1).

Many regional rivers had hydrologically stressful conditions similar or worse than the Yellowstone River in 2016, yet there were no documented PKD fish kills. These results indicate that *T. bryosalmonae* is widely distributed and suggest that warm temperatures and low flow conditions cannot alone explain PKD-caused fish kills. This unanticipated die-off further underscores our limited understanding of PKD. Focused monitoring of PKD disease dynamics is required to better understand how stressors interact to result in PKD mortality events.

## A Framework for Monitoring Fish Diseases

The health of fish populations is subject to a wide-range of biotic and abiotic factors. Tracking patterns in fish disease or parasite prevalence, therefore, may serve as an integrative measure of ecosystem health not revealed though tracking physical vital signs (e.g., flow and water temperature) alone. Traditional fish health surveys typically involve lethal sampling of fish so that tissues can be diagnosed in the lab. Diagnostic approaches include visual identification, culture-based methods, and, more recently, molecular techniques.

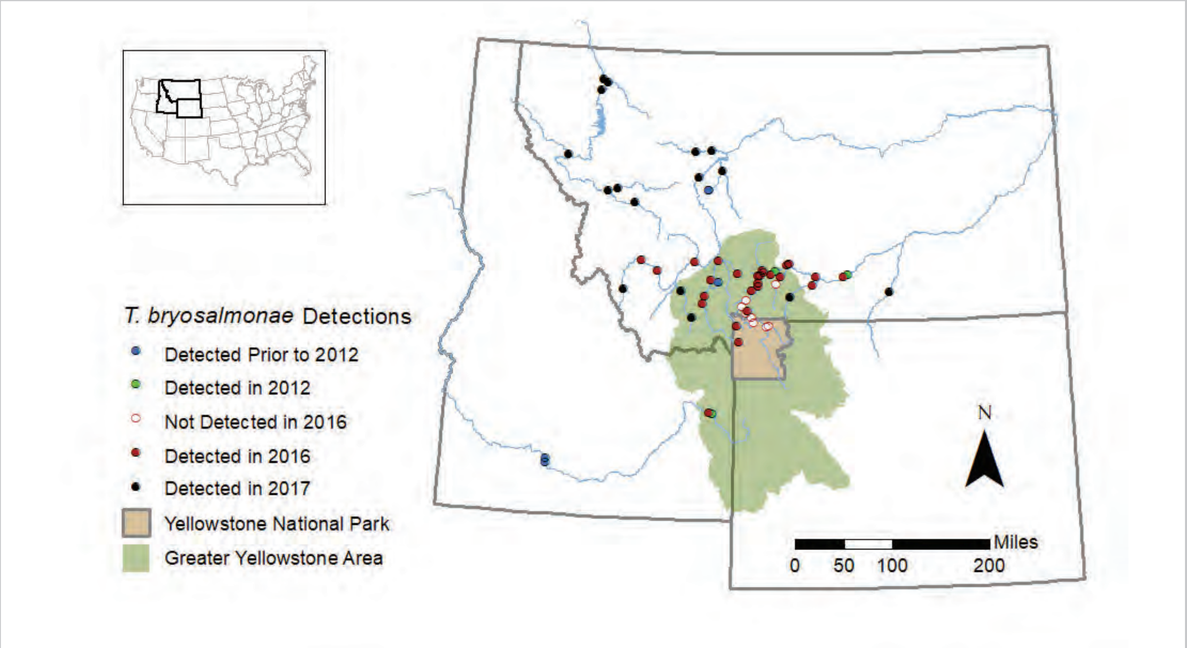

**Figure 1. All known detections of *T. bryosalmonae* in fish tissue inferred from either microscopic, histological, or molecular detection methods.**

Environmental DNA (eDNA) approaches, however, can detect target strands of DNA that are freely available in the environment. Sampling water, rather than fish tissue, can be used to noninvasively monitor natural waters for the presence of infectious diseases and with less expense and labor than traditional sampling (Huver et al. 2015). Parasite detection in water involves filtration of easily collected water samples that are then used in downstream molecular diagnostics. However, detecting parasite DNA in water does not imply the presence of a viable parasite population or indicate widespread infection in fish at that location. For this and other reasons (e.g., relative low cost), eDNA should not be used as the sole line of evidence for fish disease, but should be used as a monitoring tool that informs more intensive sampling efforts.

Surveys for parasite DNA in water can be used to inform research and management efforts at varying temporal and spatial scales. For example, eDNA samples collected at USGS streamgages can pair parasite DNA detections and environmental conditions over large temporal and spatial scales, while eDNA samples collected along transects spanning several river miles may help identify parasite "hotspots" at smaller temporal and spatial scales. Both sampling strategies can be used in isolation or in concert to inform and enhance how the NWFHS is implemented. Patterns in parasite detection can, for instance, inform targeted fish collection for tissue screening to determine the prevalence and severity of infection in sampled fish. Using eDNA, therefore, has great potential to add power, flexibility, and utility to existing fish health and vital sign monitoring programs.

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# Insects as a Vital Sign in the Greater Yellowstone Ecosystem

*by Diane M. Debinski*

Insects far outnumber vertebrates in Yellowstone National Park (YNP), North America, and worldwide. In fact, 80% of all named species are invertebrates (Cardoso et al. 2011). Despite their abundance, ecological importance, and benefits to society, numerous opportunities for discovery and for elevating the understanding of insects' contributions to health of ecosystems still remains. For example, even in well-studied places like YNP, studies of invertebrates often reveal previously undocumented species (Duffy 1999). Because of the growing need for clear and reliable indicators of ecosystem change, monitoring programs are increasingly relying on insects to provide biological evidence of ecosystem health. Insects are excellent indicators because they are relatively easily collected, have a short life span, a high reproductive rate, and great mobility in the environment. Because of these traits, insects react quickly to environmental changes. Insect development is affected by humidity, rainfall, and temperature (Kremen et al. 1993), making them sensitive to even the smallest changes in local habitat. Some insects may have short dispersal distances despite being winged. These types of species are some of the first to be affected under conditions of habitat loss or fragmentation (Sobrinho et al. 2003).

## The Ecological Role of Insects

As a result of the co-evolution of plants and insects, the two are dependent on one another for survival. Insects provide pollination services to the majority of flowering plants (Waldbauer 2003), and many of these relationships are so specialized that in the absence of its pollinator a plant cannot reproduce. Conversely, in the absence of its food source an insect will not survive. Although bees (Hymenoptera) are the most common insect involved in pollination, flies (Diptera) are a close second (Larson et al. 2001). The associations between flies and flowers are commonly overlooked, but their role in pollination increases with increasing altitude, making flies important pollinators in sites like alpine meadows of the Greater Yellowstone Ecosystem (GYE). Seed dispersal is another example of the delicate symbiosis between plants and insects. In fact, 35% of flowering plants rely on ants for seed dispersal (Waldbauer 2003).

Insects provide a vital connection between plants and vertebrates. Without insects, many food chains would collapse. Herbivorous animals, most of which are insects, play a pivotal role as intermediaries in food chains by making the nutrients in plants available to animals that do not eat plants (Waldbauer 2003). During the dry summer months when grizzly bears in YNP are stressed for food, insects become an important part of their diet; Yellowstone grizzly bears are one of the only North American populations that consume insects in noteworthy amounts. Consumption of bees, wasps, and army cutworm moths (*Euxoa auxiliaris*) increases as higher-quality foods decrease in availability during August and September (Mattson 2002). Insects also regulate vertebrate populations through insect-borne diseases, parasitism, and herbivory competition. For example, ticks may cause significant blood loss, excessive scratching, and disrupt the eating patterns of their vertebrate hosts (Mooring and Samuel 1998).

Insects aid in the crucial process of nutrient cycling by moving soil, consuming carrion, and decomposing organic matter. Insect activity physically modifies the soil profile, improving the habitat for plant growth. Ants and other burrowing insects redistribute soil, bringing mineral-rich components from below and mixing it with organic matter, creating a fertile environment ideal for plant growth. In an area such as the GYE with large populations of large mammals, carrion decomposition is a significant issue. Carrion beetles are especially important in decomposition. Sikes (1994) found more than 50 species of carrion beetle present in the northern range of the GYE that are heavily dependent on ungulate carcasses.

## Justification for Monitoring Insects As Indicators

Changes in insect populations are detectable in other levels of the food chain. For this reason, monitoring insect populations allows the prediction of effects on animals at higher levels in the food chain. Several groups of insects have been used to document long-term changes in habitats (Turin and den Boer 1988), and fossil records of insect communities have been used to construct climate histories (Atkinson et al. 1987). Because insect populations are responsive to habitat changes at both small- and large-scales (e.g., climate change, fire, or exotic species outbreaks), their use as biological indicators could offer a richer understanding of ecological change in YNP and across the GYE.

**Figure 1.** *Parnassius clodius*, **a montane meadow butterfly whose eggs hatch when the snow melts, is an excellent indicator of how snowmelt date affects insect population dynamics. This individual was marked with a number as part of a population study in Grand Teton National Park.** PHOTO - ©K. SZCODRONSKI

**Climate Change:** Insects are especially responsive to climate change because of their specialized habitat requirements. For instance, butterflies have shown rapid responses to climate change (e.g., Warren et al. 2001). The implications of changes in climate for butterflies are potentially serious, with particular concern expressed about montane butterfly communities where habitats are predicted to shrink. Many butterflies in the GYE are tightly correlated with specific meadow habitats and already show population changes associated with drought (Debinski et al. 2013). Drought-induced change may portend future climate-induced shifts to butterflies and other montane insects.

**Fire:** For species that predominantly live above ground, direct effects of fire can include incineration. In contrast, for species that live underground (ants, burrowing beetles, or other insects overwintering underground), there may be few, if any, direct effects of a fire. However, indirect effects of fire manifest themselves via the effects of fire on the vegetation insects use. For terrestrial insects that use dead wood, such as pine bark beetles, fire can produce a major boom in population growth (Sullivan et al. 2003). Given the predominance of lodgepole pine in YNP and across the GYE, these insects could be considered significant ecosystem engineers.

**Exotic species:** Exotic species, especially exotic plants, may be having large, yet undetected effects on terrestrial insects in the GYE. Roadways and hiking trails are primary areas for the introduction of exotic plant species because they are often transported via humans or horses. Some of the major exotic plant species in the GYE are dalmatian toadflax, spotted knapweed, Canada thistle, ox-eye daisy, houndstongue, and leafy spurge ("Invasive Plants as Indicators of Ecosystem Health," this issue). These species have indirect effects on the insect community by changing the amount and relative abundance of plants and soil nutrients available to insects (Ehrenheld 2003). These changes may increase some insect species by providing additional nectar, food, or host plants; others may decrease because their preferred nectar, food, or host plant species are out-competed by the exotics (Levine et al. 2003).

Currently, there is no park- or region-wide monitoring program tracking changes in insect populations or communities across the GYE. Yet, this taxonomic group represents a wealth of relatively unexplored vital signs of ecosystem change. Impediments to the development of a monitoring plan for this species-rich group are significant (Cardoso et al. 2011). However, guidance and selection criteria for indicator ideas and broad-scale monitoring for large protected areas have already been developed (McGeoch 1998). The diversity and distributions of these charismatic microfauna should be considered a critical source of future insight for understanding habitat and ecosystem-level changes across YNP and the GYE. This valuable insight should compel us to explore future strategies to improve the awareness of insect diversity, formalize programs to monitor changes, and consider efforts to enhance insect conservation.

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# Aquatic Vascular Macrophytes as Vital Signs: Ecological Importance & Management Considerations for the GYE

*by C. Eric Hellquist, C. Barre Hellquist, and Heidi M. Anderson*

***Myriophyllum quitense*** **and** ***Stuckenia*** **X** ***suecica*****, Firehole River. August 14, 2014.** PHOTO: C. ERIC HELLQUIST.

Large, readily visible plants (macrophytes) are central species of aquatic ecosystems. Macrophytes have diverse morphological and ecological strategies for living in divergent ecological conditions or niches that span the water column. For example, macrophytes can be free-floating on the surface, entirely or partially submerged, and emergent. Of the 41 vital signs selected for Yellowstone National Park (YNP), nearly two of every five (40%) can be connected to macrophytes (table 1; Jean et al. 2005).

Macrophytes respond to external conditions (e.g., climate, hydrology, and site productivity) yet also create conditions that define habitats for other biota (table 1). Waterfowl (Squires and Anderson 1995) and some mammals (McMillan 1953) use macrophytes as important food sources. Macrophytes are substrate for algae and other microscopic organisms (Pip and Robinson 1984) and provide habitat for fish nesting, egg attachment, and shelter (Dibble et al. 1996). Like amphibians (e.g., McMenamin et al. 2008), macrophytes also can provide clues of distressed populations and habitats.

Since 2008, the macrophyte diversity of YNP and Grand Teton National Park (GTNP) has been inventoried (Hellquist et al. 2014). Comprehensive field surveys have located more than 90 species of macrophytes in YNP and over 70 species in GTNP. Over 2,100 unique specimens have been obtained from approximately 390 field sites in YNP, GTNP, and the National Elk Refuge near Jackson, WY. Many collections are range expansions and new records for the Greater Yellowstone Ecosystem (GYE; Hellquist et al. 2014). These records document aquatic communities ahead of exotic introductions (Westbrooks 2004) and serve as mileposts of succession as wetland and aquatic habitats contract in a projected drier future for the GYE.

As of 2016-2017, no non-native, entirely aquatic invasive macrophytes (Roper 2017, Hellquist et al. 2014) have been detected in YNP or GTNP; however, three exotic wetland species (*Nasturtium officinale* W. T. Aiton, *Myosotis scorpioides* L., and *Mentha spicata* L.) were observed. Invasive macrophytes are abundant throughout the lower 48 states and easily spread by people. The absence of invasive macrophytes in YNP and GTNP is remarkable. Their absence in YNP and GTNP is due in large part to the vigilance of National Park Service boat inspections and good fortune.

**Table 1. Vital signs for Greater Yellowstone parks with connections to macrophytes. Factors that are created or provided by the macrophytes themselves (MACRO) as well as external factors (EXT) that influence macrophyte abundance are noted. Table adapted from Jean et al. 2005.**

| LEVEL 1 | LEVEL 2 | VITAL SIGN | CONNECTION |
|---|---|---|---|
| **AIR & CLIMATE** | **Weather** | Climate | Loss of habitat due to increased aridity (EXT); esp. Northern Range, Lower Geyser Basin, Hayden Valley, Bechler |
| **GEOLOGY & SOILS** | **Geomorphology** | Stream sediment transport | Enhanced sediment capture (MACRO) and reduced floor (MACRO) |
| **WATER** | **Hydrology** | Ground water quality | Reduced habitat availability with decreased water tables (EXT) |
|  |  | Biogeochemical flux and water chemistry | Productivity (MACRO), nutrient cycling (MACRO/EXT), and species distributions (MACRO/EXT) |
|  | **Water quality** | Algae | Periphyton abundance and substrate (MACRO) |
|  |  | Aquatic invertebrate assembiages | Food or substrate (MACRO) |
|  |  | Water temperature | Shading (MACRO), e.g. by stands of *Myriophyllum sibiricum* , *Nuphar polysepaia* , *Potamogenton* |
|  | **Invasive species** | Present of aquatic invasive plants | Altered habitat structure and biotic interactions (MACRO) |
|  |  | Exotic aquatic assemblages | Altered habitat structure and biotic interactions (MACRO) |
| **BIOLOGICAL INTEGRITY** | **Biological integrity** | Riparian/riverine | Taxa primairily or exclusively in flowing water, e.g., *Myriophyllum quitense* , hybrid *Potamogeton* taxa (EXT) |
|  |  | Insects | Habitat structure (MACRO), reporductive substrate (MACRO), and forage (MACRO) |
|  |  | Beaver | Habitat expansion (EXT), plant community succession (MACRO/EXT), forage (MACRO) |
|  |  | Amphibian | Habitat structure (MACRO) |
|  |  | Native aquatic assemblages | Habitat structure (MACRO), trophic interactions (MACRO) |
|  |  | Ungulates | Forage, esp. moose (MACRO) |
|  | **All risk biota** | Birds of concern | Forage and habitat for Trumpeter Swans and other waterfowl (MACRO) |

In 2017, more than 3,500 vessels from 47 U.S. states were inspected in YNP alone (Roper 2017). Fifty-six vessels were decontaminated, several of which carried macrophytes. An added benefit of boat inspections was educational outreach to approximately 10,400 visitors (Roper 2017).

Boat inspections are crucial for intercepting human-mediated introductions, but aquatic invasive species (AIS) can arrive via animals as well. Waterfowl regularly disperse macrophyte vegetative structures or propagules (Brochet et al. 2009) and may introduce AIS from waters outside of the parks. Continued monitoring and an established rapid response plan will be critical to address the arrival of AIS. A proactive plan would outline protocols (e.g., waterfowl or wildlife surveys, containment standards) so action can be taken if a nascent invasion is discovered. Surveys should be concentrated in areas with the most boat use and fishing activity and where migratory waterfowl congregate. Ideally, these surveys would be coordinated with ongoing fisheries and amphibian monitoring efforts at multiple, overlapping sites.

Low temperature hydrothermal areas are also a potential habitat of concern for AIS and merit consideration for regular monitoring. Some hydrothermal habitats could provide refugia for invasive southern taxa or unique genetic forms (i.e., genotypes). For example, an unusual population of the macrophyte *Najas guadaloupensis* has been long established in Kelly Warm Springs, GTNP. Based on the abundance of exotic aquarium fish at Kelly Warm Springs (Harper and Farag 2017) and the unusual genetic identity of this *Najas* population, it's highly probable that the *Najas* population may have originated from discarded aquarium plants.

An emerging management tool that provides promising opportunities is environmental DNA (eDNA). Isolated from water samples, eDNA can provide evidence of invasive macrophyte colonization and potentially the relative biomass of populations (Matsuhashi et al. 2016). Genetic signatures of high-risk invasive macrophytes such as Eurasian water milfoil (*Myriophyllum spicatum* L.) could be targeted. The use of eDNA could be a time and cost efficient method to detect an unfolding invasion.

While preventing invasive macrophytes from entering YNP requires a commitment of time, funds, and personnel, it is a wholly worthwhile investment (Leung et al. 2002, Westbrooks 2004). Proactive efforts are less financially and logistically expensive than trying to manage macrophyte invaders once they colonize. Because asexual propagation of most invasive macrophytes makes eradication unlikely, early detection is essential. Once established, treatment options become complicated by ecological, logistical, economic, and political concerns.

Additional funding for invasive macrophyte monitoring and management could originate from a number of sources, such as park entrance fee revenue or recreational permit fees. A more extreme measure could be suspension of motorized boat use by visitors. Alternatively, visitors could be restricted to using watercraft that are overseen by the park and do not leave YNP waters. These options would be controversial, but would reduce a major introduction pathway for invasive macrophytes and other AIS. If employed, resources formerly used for boat inspections could be reallocated to macrophyte field surveys and regular monitoring.

The aquatic and wetland habitats in the GYE contain diverse native macrophyte assemblages. These plants are important for their foundational role as the basis of the food chain and their extensive ecological interactions. Meanwhile, the potential for invasive macrophytes to enter the GYE is a looming, formidable concern for the conservation and management of regional aquatic ecosystems. Continued research and monitoring will improve our understanding of the role and importance of macrophytes in aquatic ecosystems and will alert park managers to the unwelcome potential arrival of invasive species.

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**C. Barre Hellquist**, (right) Professor Emeritus at Massachusetts College of Liberal Arts, has been studying the ecology and systematics of aquatic plants for over 45 years. Much of his research has focused on pondweeds (Potamogetonaceae) and water-lilies (Nymphaeaceae). His field studies have been concentrated in North America, Australia, and Russia. He and his son Eric have been documenting the aquatic plant diversity of the Greater Yellowstone Ecosystem since 2008.

# Invasive Plants as Indicators of Ecosystem Health

### *by Stefanie D. Wacker*

**Looking northwest from the North Entrance of Yellowstone, the town of Gardiner, Montana, on the right. The yellow hue is blooming desert alyssum, a very invasive winter annual that has significantly expanded in the last decade, largely in the drier parts of the park, but has been found in Lamar and Hayden valleys. Photo taken April 15, 2017.** (NPS PHOTO - S. WACKER)

Healthy, native plant communities provide sustainable habitat for wildlife, insects, and soil biota. They can persist through drought and contribute to ecosystem services, such as clean air and water. When invasive species are introduced into a native plant community, there can be numerous deleterious effects with minor to major consequences. For example, a non-native species might co-exist with only minor influence on the community or be highly invasive and cause major, wholesale community change. In the latter instance, invasive species can out-compete native plants for water and nutrient resources, have prolific seed production with high viability, and benefit from highly plastic life strategies which allow them to maximize resources. Long-term monitoring of plant communities in Yellowstone National Park (YNP) has numerous benefits, but principally, knowledge gained in the patterns and process of invasive species that threaten the native flora and compromise important ecosystem processes. Currently, there are 225 exotic plant species in the park, which represents approximately 15% of the taxa recorded (Whipple unpublished), a 50% increase from what was reported in Hansen et al. (2014). However, this is a measure of the number of recorded species and not the percent of vegetation cover. Long-term monitoring data can be used to assess the actual area covered by individual species. Additionally, information gained can be used to set priorities and guide landscape-level and species-specific management strategies, evaluate treatment efficacy, and identify specific disturbances that can lead to plant invasions (Blossey 1999).

Long-term monitoring of vegetation communities also helps in developing the state and transition model for different plant communities (e.g., sagebrush steppe, wet meadows, lodgepole forest) as well as identifying unique environmental stressors. In each community, the "state" of each community is represented by current species composition and abundance. The "transition" represents an in-between state where a change in species composition and/or abundance is triggered by one or more disturbances. State and transition models illustrate the resistance and resilience of a plant community to disturbances (Chambers et al. 2014). An example in the sagebrush steppe community would be a shift from sagebrush dominant with native, cool-season grass understory to an exotic, winter-annual understory, triggered by disturbances such as abandoned bison wallows or social trails. The scale of these changes can remain localized or progress to a landscape scale. The ability for a community to resist significant compositional change can be greatly affected by the type of disturbance and the presence, abundance, and biology of non-native species. These characteristics also affect the resilience, that is, the ability of a community to return the previous, pre-disturbance state.

NPS PHOTO: S. WACKER

In 2015, a sagebrush steppe monitoring program was initiated in the northern range, Hayden Valley, and Pelican Valley in YNP. The silver sage (*Artemisia cana*) and big sage (*A. tridentata, sensu lato*) communities make up roughly 7% of the park, with big sage occupying the drier sites. However, computer models predict big sage could expand into novel locations, driven by both climate and exotic plant invasions (Bradley 2010, Bradford et al. 2014). Through careful inventory, National Park Service (NPS) scientists developed a list of native and non-native species in both the big sage and silver sage vegetation types. The monitoring program is designed to detect changes in frequency and abundance of both native and non-native species, with a particular interest in the current populations as well as identifying introductions of non-natives. By tracking numerous species, valuable information is gained regarding fluctuations in species abundance and can link spatial distribution with climate conditions, past disturbance, patterns of plant invasions, and other environmental, topographic, and edaphic gradients. Long-term vegetation monitoring is critical in this time of rapid climate change to better understand the complexities of the sagebrush steppe and to anticipate the future changes in species distribution. This knowledge will also prepare us for the transition to novel communities and give insight to the environmental conditions which may be drivers of change. Novel communities are unique assemblages of plants and associated biota that are the direct result of human-related impacts which drive communities beyond ecological thresholds and result in the transition to new, alternative states that are unlikely to return to a previous or historic state (Morse et al. 2014).

In order to anticipate and mitigate the effects of rapidly changing climate, YNP must continue to invest in long-term monitoring of plant communities. The dry sagebrush communities of Yellowstone are particularly susceptible to unprecedented invasions by winter annual grasses and forbs, specifically annual wheatgrass (*Eremopyrum triticeum*), cheatgrass (*Bromus tectorum*), and desert alyssum (*Alyssum desertorum*). Having witnessed complete community change in the Gardiner Basin in less than 30 years, it is clear that rapid and large-scale changes in other parts of the northern range are possible. While the arid conditions of the Gardiner Basin combined with a long history of varied land use is not replicated elsewhere in the park, it does illustrate the ability for non-native winter annuals to outcompete most native and even other non-native species in arid and/or drought conditions. Because these dry sagebrush communities are at high risk for catastrophic plant invasions, nine long-term monitoring locations have been established between the park boundary at Beattie Gulch and Mammoth Hot Springs. Figure 1 shows the proportion of desert alyssum in each foliar cover class (an estimation of abundance; follows Daubenmire 1959)

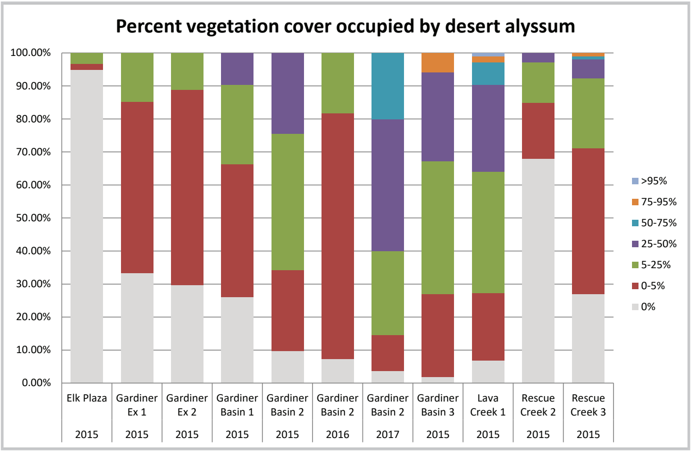

**Figure 1. The proportion of desert alyssum (Brassicaceae: *Alyssum desertorum*) vegetation cover at nine long-term monitoring sites. Vegetation cover is collected in 50-100 1-m$^2$ sample plots. Data for approximately 100 species is collected at each study site. Desert alyssum was selected to monitor because of its ability to become extremely invasive. It is the most widespread and has the highest vegetation cover of the winter annuals in YNP.**

at each location. Desert alyssum plus other winter annual species threaten other parts of the park, such as Lamar and Hayden valleys, particularly under the stress of projected climate scenarios of warmer, drier conditions. Only through consistent, continued monitoring will NPS scientists be able to detect the changes and determine ecological thresholds that when crossed, can result in potentially irreparable change to critical habitat.

Even though invasive species have plagued YNP for decades, we are now in a period of rapid environmental change, as well as increased threat by ever-expanding invasive species populations. A dedicated, long-term vegetation monitoring program is the best way to understand the state, transitions, and stressors of our sagebrush plant communities. Combining field collected data with remote sensing techniques such as those described by Thoma et al. ("Patterns of Primary Production and Ecological Drought in Yellowstone," this issue) allows us to quantify the magnitude of change and adjust management to help sustain the wild landscapes that define Yellowstone as the nation's first national park.

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# An Uncertain Future: the Persistence of Whitebark Pine in the Greater Yellowstone Ecosystem

### *by Erin K. Shanahan*

Figure 1. Located in the Wind River Range, the whitebark pine that captured author Erin Shanahan's heart. Field technicians attempt to measure the majestic tree's diameter at breast height. (July, 2018; NPS PHOTO - E. SHANAHAN).

If ever I was to love a tree, this is the tree (figure 1) that would own my heart. Enduring gracefully at the base of a narrow, high-elevation cirque in the Wind River Range, it is a challenging off-trail scramble to be in its presence. My first encounter with this massive whitebark pine was in July 2014. Located just a stone's throw from our monitoring plot, I felt compelled to pay homage to this incredible specimen that has clearly withstood hardship. While I do not know its age, I would posit this towering whitebark pine has been rooted in this location for more than 500 years. The extensive fire scar at its base, combined with its age, confirm that this timeworn tree has survived periods of immense environmental stress.

Throughout the past decade, I have personally witnessed the death of thousands of whitebark pine trees due to the voracious appetite of a diminutive, native bark beetle, the mountain pine beetle. How this tree and its neighboring whitebark pine have escaped beetle attack astounded me. In addition, the pathogen white pine blister rust had yet to infiltrate this oasis. While this individual has stood tall and chronicled the story of environmental change within its tree rings, others of its species have been less fortunate.

Whitebark pine is considered a keystone and foundation species that exerts strong influences on the biodiversity and productivity of high-elevation and subalpine communities in the Pacific Northwest and northern Rocky Mountains. Because of these traits and the multiple concurrent threats it faces, the selection of whitebark pine as a regional, cross-jurisdictional (e.g., Bureau of Land Management, National Park Service, and U.S. Forest Service) vital sign has been widely embraced.

## Whitebark Pine Declines

Substantial declines in whitebark pine have been documented throughout its range (Logan et al. 2009). Decreases can be attributed to a number of factors acting individually or in concert: mountain pine beetle, white pine blister rust (caused by the introduced fungus *Cronartium ribicola*), more frequent and intense wildfires ("Nowcasting and Forecasting Fire Severity in Yellowstone," this issue), and climate-induced drought. These agents all pose significant risk to the persistence of whitebark pine populations on the landscape; as a result, whitebark pine was listed as a candidate species under the Endangered Species Act in 2011.

Mountain pine beetles are one of most aggressive and damaging bark beetles of western pine forests (RMR, FHP 2010). The behavior of mountain pine beetle is strongly tied to temperature (Jewett 2010). For the most part, temperature constraints have, until recently, limited mountain beetle to lower elevations (Logan and Bentz 1999, Bentz et al. 2010). Cold temperatures have also restricted mountain pine beetle to a life cycle that requires multiple years to complete a generation (Logan and Powell 2004, Bentz et al. 2015). Historically, cold, high-elevation temperatures prevented synchronized outbreaks of mountain pine beetle, thus keeping the beetles and whitebark pine trees separated (Raffa et al. 2013). But recent warming at whitebark pine elevations has enabled beetles to move upslope and attack whitebark pine, a species that, from an evolutionary perspective, did not have to evolve strong defenses to combat beetles (Raffa et al 2013). From 2006 to 2008, above-average temperatures exceeded a cumulative temperature threshold, enabling mountain pine beetle to shift from a multi-year to a single-year life cycle, expediting reproduction (Carroll et al. 2006). This collapse from a multi-year to single-year life cycle resulted in large, synchronized attacks on whitebark pine.

## The Perfect Storm

The 2006-2008 warming period combined with an abundant food supply was the "perfect storm" for the eruption of mountain pine beetles at epidemic levels across the Greater Yellowstone Ecosystem (GYE). The Greater Yellowstone Inventory and Monitoring Network's monitoring program documented a steady increase in mountain pine beetle-associated mortality with a substantial increase in recorded deaths of monitored trees from 2008 to 2009. In 2009, an early season cold snap likely killed mountain pine beetle larvae before they had become cold hardened (Dooley and Six 2015, Shanahan et al. 2016). The consequences of this weather event and a significantly depleted food supply (beetles had literally eaten themselves out of house and home) in many areas of the GYE likely returned mountain pine beetle populations to pre-warming or endemic levels. Unfortunately, the mortality attributed to the three-year mountain pine beetle outbreak resulted in an overall reduction in the number of larger, reproducing trees and a shift to smaller-sized, typically non-reproducing trees in the remaining whitebark pine stands (figure 2; Shanahan et al. 2016).

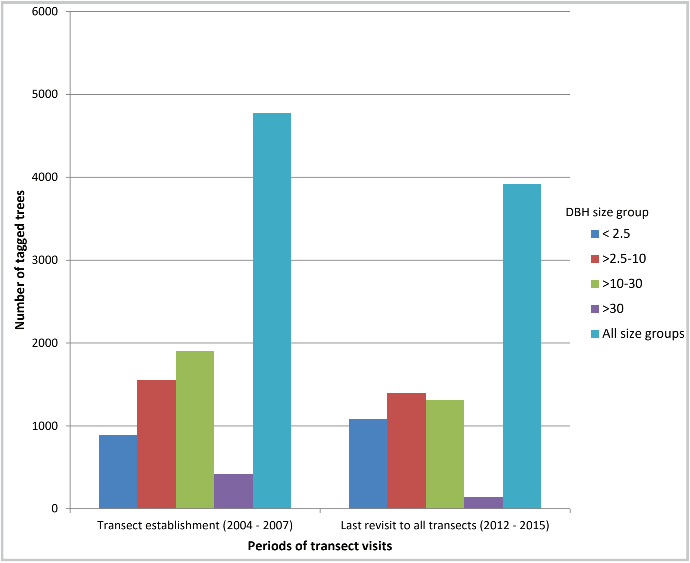

**Figure 2. Live tagged trees by size class group according to diameter at breast height (DBH) in the transect establishment period (2004-2007) compared to the more recent survey visits (2012-2015). The change in tagged tree numbers results from the combination of recruitment and mortality.**

Unlike the rapid mortality due to mountain pine beetle, white pine blister rust (blister rust) infection is more gradual but potentially as lethal. Blister rust infection is ubiquitous throughout the GYE, with infection levels varying across the region (Shanahan et al. 2017). Temperature and moisture are key factors in blister rust dispersal and successful infection (Kendall and Keane 2001). Infections typically initiate when airborne spores enter open stomata in needles near the crown or top of a tree. Over time, an infection can expand or transition from the needles to an adjacent branch and eventually to the trunk or bole. Bole infections are generally more debilitating or lethal to the tree (Campbell and Antos 2000, McDonald and Hoff 2001). Once infected, smaller whitebark pine have a greater likelihood of mortality than larger trees (Shanahan et al. 2016). Smaller trees may be more susceptible because they have fewer and shorter branches, which reduce the distance an infection has to travel from branch to bole. In comparison, larger trees may resist infection expansion by shedding branches or "walling off" infections (Tomback et al. 1995).

## Uncertain Future

There are contrasting hypotheses on the vulnerability of understory whitebark pine to blister rust exposure and the mechanisms affecting infection transmission. Some have hypothesized that infection is less likely in smaller trees, which are smaller targets and benefit from an umbrella-like protection by the overstory (Campbell and Antos 2000, Smith and Hoffman 2000, Kearns and Jacobi 2007). Others suggest the microclimate within the understory of an intact stand plays a critical factor in increasing susceptibility to infection transfer by trapping and increasing humidity (Tomback et al. 1995, Smith et al. 2008, Mahalovich 2013). The

**Whitebark pine cones are egg shaped and distinctly purple in color.** (NPS PHOTO - E. SHANAHAN) recent mortality of large whitebark pine trees has fragmented the overstory canopy in stands across the GYE. As a result, if the first hypothesis is correct, an overall increase in blister rust infection of understory whitebark pine where the sheltering qualities of an intact, multi-structural forest have been disrupted may be seen. Alternatively, if the second hypothesis is correct, the loss of upper canopy trees may have the effect of altering the understory environment such that the critical conditions necessary for the complex transfer of blister rust spores to susceptible understory hosts is now less favorable (open canopy and decreased humidity). This presents an interesting situation where the impacts of the recent mountain pine beetle outbreak may facilitate or, conversely, impede the future dispersal patterns of blister rust in the remaining whitebark pine population.

Though multiple factors contribute to a tree's susceptibility to infection and the likelihood that an infection moves from one part of a tree to another, environmental conditions play a substantial role. For example, weather conditions affect many aspects of blister rust transmission, and within the GYE these conditions can vary temporally and spatially (Mahalovich 2013). Seasonal fluctuations in weather patterns not only enhance (i.e., warmer temperatures at higher elevations create a longer growing season) or hamper (i.e., colder temperatures shorten the growing season) blister rust spore development and dispersal but can also promote or inhibit infection transition on an infected tree (Kearns et al. 2009). From 2004 to 2015, I documented larger trees transitioning from a canopy-infection to a bole-infection at a high rate (48% of monitored trees in our study; Shanahan 2015). Furthermore, among smaller sized canopy-infected trees, there was a 50% chance that a canopy infection expanded to the bole in just a four-year time span (Shanahan 2015). While infected whitebark pine can persist for decades, bole infections negatively impact overall vigor and reproductive potential by precluding the flow of vital nutrients necessary to sustain normal tree functions, healthy foliage, and cone production (Maloney et al. 2012).

In recent years, whitebark pine populations across its range have been compromised by the impacts of mountain pine beetle, blister rust, wildfire, and climate-induced drought. For some regional and local populations, conditions at or nearing an ecological tipping point may exist. In an ecological context, a tipping point is an irreversible change from one ecosystem state to another (e.g., desertification and marine fisheries collapse) such that conditions cannot be reversed. As temperatures continue to climb across all elevations of the GYE, the temperature-induced changes to the mountain pine beetle reproductive cycle coincident with the massive mortality of large trees witnessed from 2006 to 2008 may be the new normal. All remaining trees are susceptible to blister rust, and warming conditions are also likely to bring hotter and more frequent fires (Westerling et al. 2006). If conservation management actions designed to curb one or more of these factors are to be implemented in the GYE (GYCCWPS 2011), it is essential that scientists work collaboratively to determine the window of management opportunity so intervention can be most effective. Although some of the benefits of our region-wide monitoring program are already helping to understand the complexities of recent threats to whitebark pine, continued monitoring will serve as an enduring resource for decision makers today and into the future.

In July 2018, I revisited the enclave where my favorite whitebark pine resides, returning with mixed emotions and some hesitation. On the hike out in 2014, I came across an active mountain pine beetle outbreak a mere 300 feet (91 m) downslope from this untainted stand. Given my knowledge of the dispersal capabilities of mountain pine beetle, my fear was that even this astounding monarch may succumb to a fatal attack. Well, my anxiety was for naught (figure 1); I will keep my fingers crossed until my next visit in 2022.

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# Past Warm Periods Provide Vital Benchmarks for Understanding the Future of the Greater Yellowstone Ecosystem

### *by Cathy Whitlock & Steve Hostetler*

The wildlife, vegetation, and ecosystems discussed in this issue of *Yellowstone Science* are vital signs of the Greater Yellowstone Ecosystem (GYE) that warrant continued monitoring. Determining which organisms and processes are truly vital ecosystem components requires both an understanding of modern ecological interactions and insight into the resilience of organisms and processes to stressors in the past. The time frame for evaluating past dynamics is often short, but ideally it should be decades or longer in order to span several life cycles of particular organisms or occurrences of a particular process. In a perfect world, we would have information that covers centuries or millennia to assess the consequences of environmental changes that occur over multiple time scales before the influence of recent human activity. Such long-term insights are indeed possible through two approaches. Paleoecological, geological, and archeological data can be used to reconstruct biotic and landscape history. Climate and ecological models help identify the mechanisms linking physical and ecosystem processes in the past and provide simulations of plausible conditions in the future. The challenge with incorporating a paleo-perspective into a discussion of vital signs is that the past is incompletely known and seen through an imperfect lens. Ecological phenomena of interest in the present are often poorly registered over longer time scales.

Future climate projections for the GYE suggest that mean annual temperatures will be 6°F-13°F (3°C-7°C) higher by the end of the century, and warming will occur throughout the year (figure 1). Winters will be wetter but with a transition to more rain instead of snow, and summers will be drier (figure 1). The changes in temperature and precipitation will have many consequences—earlier snowmelt and peak runoff, shorter springs, less water for streamflow and soils in summer, and greater deficits in evaporative demand, which

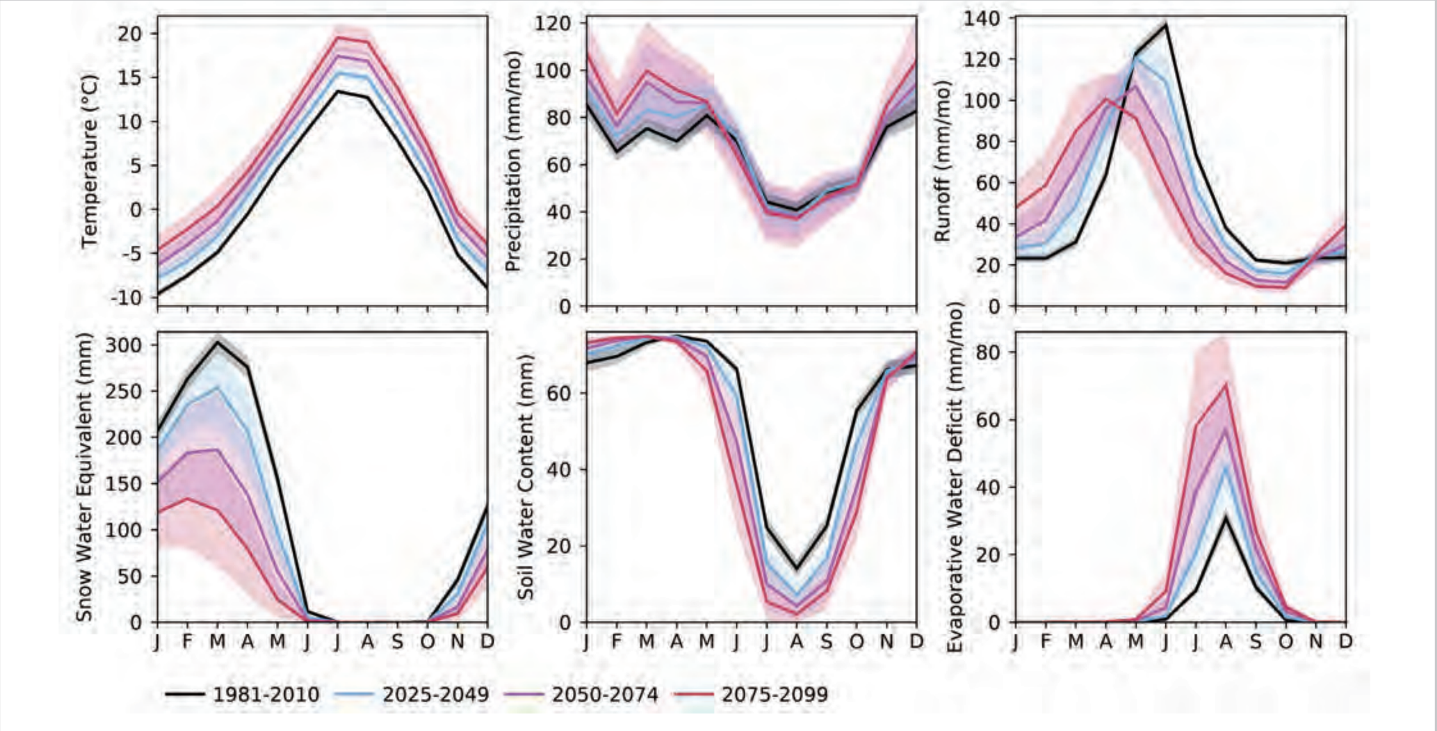

**Figure 1. Future projections of climate and hydrology in GYE, plotted by month. Air temperature and precipitation are the averages for 30 climate models participating in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). Runoff, snow water equivalent (SWE) for April 1, soil water content, and evaporative water deficit (the amount of water that would potentially be evaporated from the soil if available) were simulated with a water-balance model that used temperature and precipitation as inputs. Each colored line represents the 30-model average for the indicated 25-year period and the corresponding color shading indicates the spread in the 30 models (from Hostetler and Alder 2016).**

is indicative of more fires and fire-related erosion. Projected changes in temperature and the hydrologic cycle will alter patterns of animal movement and shift plant distribution and abundance. New organisms that are better adapted to warm conditions and frequent disturbances will move into the region, replacing those that are disturbance sensitive and drought intolerant. High stream temperatures at lower elevations will exceed critical levels for native salmonids leading to their decline, whereas presently cold streams at high elevation may warm sufficiently to support salmonids (Al-Chokhachy et al. 2013).

Three periods in the past, characterized by rapid climate change or high temperatures, serve as baselines for evaluating potential climatic and ecological change in the GYE. The first period is the late-glacial to early-Holocene transition (~16,000-11,500 years ago) when temperatures rose about 5˚F-7˚F (from -15˚C to -13˚C) at the end of the last ice age. The difference between warming then and now is that late-glacial warming occurred in summer, and the rate of warming was about 50 times slower than what has been observed in recent history. The second period is the early Holocene (~11,500-7,000 years ago) when summer temperatures were on average 3 to 4˚F (1.6 to 2.2˚C) warmer than present, and winters were colder by a similar amount, as a result of increased summer and decreased winter solar radiation in the Northern Hemisphere. Although warming in early-Holocene summers is a reasonable analog for future conditions in the GYE, the colder winters are not. The third period (800-1,200 years ago) is termed the Medieval Climate Anomaly (MCA). This interval in the GYE was characterized by years to decades of extreme drought. These three benchmark periods represent a set of warm periods by which to assess whether or not current climate conditions and ecosystem dynamics in the GYE are moving into uncharted territory.

Warming at the end of the last ice age melted the Yellowstone ice cap from its full extent, which covered most of the GYE,

into remnant alpine glaciers. In response to lengthening growing seasons and developing soils, conifers colonized areas previously covered by ice. The first conifer to appear in the GYE was juniper, probably *Juniperus communis*, which established in a relatively open tundra-like landscape. Next came Engelmann spruce, followed by whitebark pine, limber pine, and subalpine fir (Krause and Whitlock 2017). Lodgepole pine was widespread after 11,000 years ago, and Douglas-fir was the last conifer to arrive, expanding after 9,000 years ago. This sequence of forest development shows that GYE conifers have the ability to adapt to steadily rising temperatures and changes in moisture by adjusting their range and abundance. Similar biotic responses are taking place now and will continue in the future, although we are starting from a warmer baseline than in the past. Some native species may no longer find suitable climate conditions in the GYE, becoming regionally extirpated as suitable habitat shrinks, and new species (e.g., Gambel oak, western larch, ponderosa pine) may move in if opportunities for dispersal become available (Bartlein et al. 1998). A concern is that non-native weedy species may benefit the most, given their ability to respond rapidly to new environmental conditions.

The early-Holocene warm period was a time of expanded lodgepole pine forest and more Douglas-fir and aspen than at present. Paleoecological records suggest that upper treeline was at a lower elevation and lower treeline was at a higher elevation compared with today, and humans and bison utilized forests that grew above present-day treeline (Craig Lee, CU-Boulder, personal communication, 2018). Many of northern Yellowstone's small lakes and wetlands dried during the early Holocene, and fires were more frequent. Yellowstone Lake likely had thicker ice cover in winter but also experienced more rapid ice-off in spring and longer open-water conditions in fall (Thompson et al. 1998).

The five-needle pines (whitebark pine and limber pine) show a dynamic history in the GYE during the early Holocene (Iglesias et al. 2015). Following an initial period of tundra and spruce parkland, limber or whitebark pine or both became a significant component of the vegetation at all elevations from 12,000 to 7,000 years ago (figure 2). The expansion of five-needle pines was associated with heightened fire activity, pointing to the ability of these species to withstand drought and frequent burning. These pines became restricted to high and low elevations as summers cooled, winters warmed and became drier, and fires became less frequent and more severe. These paleoecological observations raise concerns that high-elevation whitebark pine forests will continue to decline as warming forces optimal habitat to ever-higher locations (Chang et al. 2014). Although the paleorecord offers evidence of robust adjustments to warmer summers in the past, we have little insight about how five-needle pines will adjust to warmer-than-present winters, a condition that has not occurred during the late-glacial or Holocene periods. This realization alone justifies careful monitoring of whitebark and limber pine populations in the years ahead.

In contrast to the dynamic history of high- and low-elevation forests, lodgepole pine forests on the central rhyolite plateaus have been surprisingly stable during the Holocene, even as climate and fire frequency have varied. This stability is due to the constraints imposed by the relatively infertile well-drained volcanic soils, which tend to limit the presence of other conifers. These lodgepole pine forests developed after 11,000 years ago, replacing a sparse grassland and/or tundra. Once established, these pine forests were unaltered by early-Holocene warm dry conditions or by fires that were 3-4 times more frequent than in recent centuries (Millspaugh et al. 2004). Such resilience suggests that lodgepole pine will persist in the GYE for decades to come, if fires do not become too frequent.

The MCA featured very short springs, and winters transitioned rapidly into summer conditions that were warmer and drier than present. Tree-ring records suggest that drought conditions during the MCA persisted for years to decades in the West (Cook et al. 2004) and led to more fires, desiccation of small lakes, an upslope shift in upper treeline, and stream incision in the GYE (Meyer et al. 1995, Millspaugh et al. 2004,). Vital species, such as beaver, also changed in distribution and abundance (Persico and Meyer 2009). Although it was relatively short in duration, the intensity of drought during the MCA is not unlike conditions projected for the future.

In summary, these benchmark periods clearly show that GYE species have been highly resilient to a range of climate conditions in the past. These species have survived periods when summers were warmer than at present and periods of prolonged and extreme drought. In addition, the vital ecological processes that we monitor today have a long history in the GYE, although their frequency and intensity have varied under different climate conditions. For example, forests have accommodated a range of fire activity in the past, and fire occurrence was several times more frequent than today during warm periods. Although this gives us some confidence in ecological resilience in the future, there are some striking differences between the past and present. We are currently experiencing winters and nights that are warmer than in recent decades. These changes, which are projected to continue, have little historical precedence in the GYE. In contrast, springs that transition abruptly into

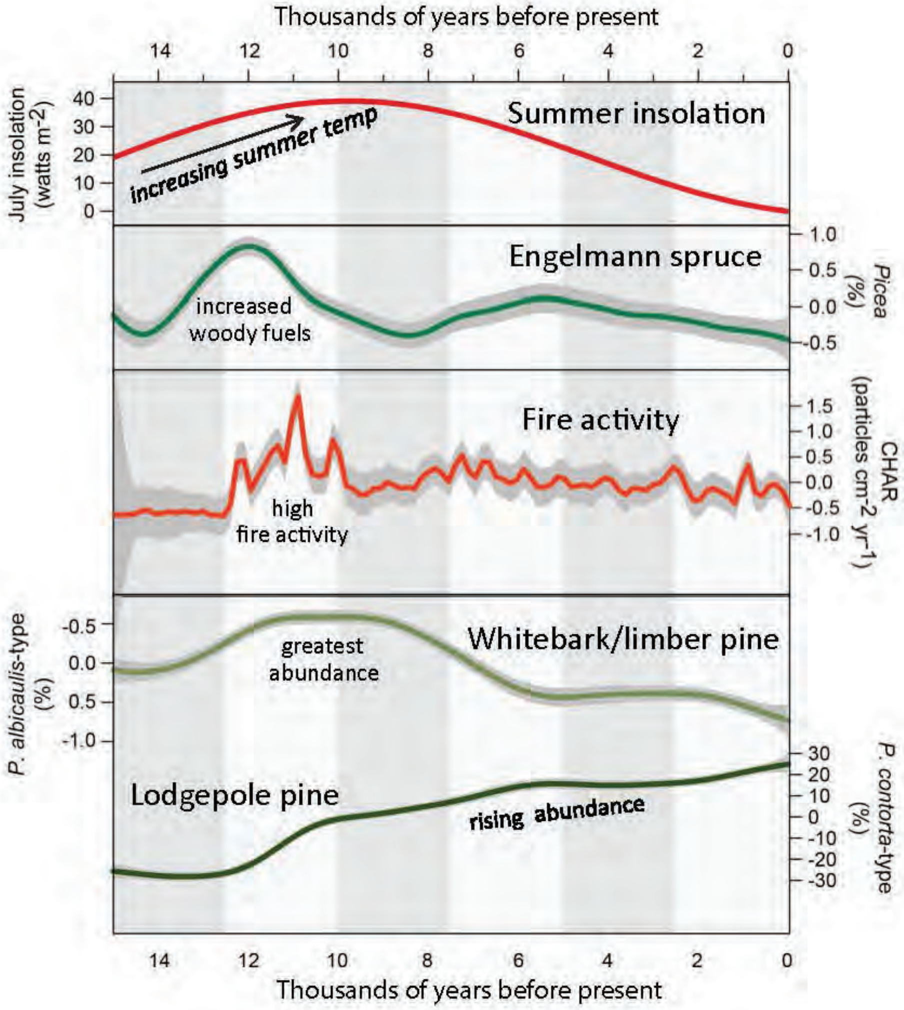

**Figure 2. Environmental and conifer history in the GYE over the last 15,000 years, including trends in July (red) insolation anomalies, generalized trends in the abundance of Engelmann spruce (*Picea* pollen), fire activity (CHAR), whitebark and/or limber pine (*Pinus albicaulis*-type pollen), and lodgepole pine (*Pinus contorta*-type pollen) from Iglesias et al. 2015. The data suggest that five-needle pines were abundant during the early Holocene (11,000-7,000 years ago), when summers were warmer and fire activity was higher than at present, and levels of competing spruce and lodgepole pine were low. This observation contributes to our understanding of how five-needle pines might tolerate warmer temperatures and increased fires in the future.**

late-summer drought, as in 2017, have occurred in the past and were likely an enduring feature of the early Holocene and MCA. Similar rapid seasonal transitions are projected for the future (figure 1), and information on past ecological responses to seasonal aridity offers clues as to how future conditions will affect plant and animal phenology, hydrology, and disturbance.

The value of monitoring vital signs in the GYE cannot be overstated. The region supports one of the last nearly pristine temperate ecosystems in the world, a place where nature largely operates as it has for millennia. Our understanding of vital signs is enhanced when we can place observations of present-day dynamics into a longer context of environmental change. Relative to other places, the postglacial history of the GYE is relatively well studied, and this information describes ecological vulnerability to a broader range of climate conditions than can be observed over a limited historical period. In some respects, the GYE is entering a period of novel climate and ecosystem dynamics, but in other ways, conditions are still within the range of long-term historical variability. For this reason, assessments of ecological thresholds, resilience, and vitality in the GYE require sustained observation of vital species and processes, and regular comparison of current conditions to past benchmarks. It is also imperative to continue parallel efforts that utilize these observations to improve ecological and climate models. Such integrated endeavors lead to a better understanding of how ecological processes interact with climate and improve our confidence when applying models to investigate past, present, and future ecological change.

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# What We're Listening To: How Sound Inventories Can Contribute to Understanding Change

### *by Jennifer Jerrett*

Do you want to get off the beaten track and experience Yellowstone in an entirely new way?

If you answered "yes," visit Black Sand Pool and turn an ear to the ground. The giant, imploding bubbles in Black Sand Pool make a low-frequency sound that you'll feel through your whole body. It's undeniably an Earth sound—a planetary sound. And listening to a hot spring is an entirely different experience than looking at a hot spring.

Or instead of wolf watching, try howl hunting in the dark. It's difficult to describe the experience of being outside with millions of twinkling stars for company and listening to the haunting sound of wolf howls bouncing off the hills around you. It's an experience like no other. Or visit this place in the winter and seek out the utter absence of sound. A silence so complete, what you'll hear mostly is the sound of your own heartbeat. You can still find such tranquility in Yellowstone.

And that's just the point. For a truly rich and unique experience, it's not always where in the park you should go, but rather what senses you let guide you. And experiencing the park through your ears is another way to enjoy a thrill.

Our sense of hearing is switched on while we are still in the womb. In fact hearing is about as fully developed for us in utero as it is for us as adults. At the same time, our other senses are either not yet turned on or are nascent and largely undeveloped.

And so that primacy—that early emergence of our sense of hearing in human development—has to be significant in terms of the role that hearing plays in our lives and how profoundly sounds contribute to learning and understanding. To think that our very unfolding of consciousness happens (for those of us who are hearing) largely through sound. And though we can choose to close our eyes, we cannot close our ears. That's a very big deal from an evolutionary biology perspective, showing that we depend on our ears—maybe even more than our eyes—for survival.

Easy to forget in this age of the selfie, we've always been creatures of sound. And we're not alone. Most organisms use sound to communicate, find food, avoid predators, or find mates. When we cover these sounds with human-caused noise, we affect those processes and alter not only the natural soundscape but modify vital elements of wild ecosystems.

Soundscapes are categorized as a vital sign in the Greater Yellowstone Inventory and Monitoring Network (GRYN) (Jean et. al. 2005). The National Park Service (NPS) Natural Sounds Program has collected acoustic data in over 100 parks. The GYRN, however, is one of the few networks that acquired sound data from park staff, Yellowstone National Park has been monitoring soundscapes for over two decades, and these efforts have cataloged an amazing diversity of sounds.

The Yellowstone National Park (YNP) soundscape monitoring program was launched in the late 1990s and early 2000s, primarily as a component of winter use planning. At the time, managers from Yellowstone and Grand Teton national parks were interested in quantifying the potential noise impacts from vehicles that travel over snow (snowmobiles and snowcoaches): where, when, and how loud was the noise? How did that compare to the ambient baseline condition of the natural soundscape? And how should park managers deal with the noise? They worked with Skip Ambrose from the then-newly-formed NPS Natural Sounds Program and Shan Burson, who was working as an acoustic ecologist in Denali National Park at the time, to develop a soundscape monitoring program for the ecosystem. Shan came on as the full-time bioacoustic ecologist for Grand Teton and Yellowstone in 2003 (Shan retired in December 2017 and recently received a Director's Natural Resource Stewardship and Science award for his outstanding work over the years. As a testament to the importance of his work, the program lives on in Yellowstone).

It's difficult to overstate how successful this program has been. One of the most notable outcomes was a comprehensive reframing of how we establish vehicular noise thresholds during the winter use season. Initially to mitigate the increasing noise impacts from oversnow vehicles (OSVs), thresholds regulated the number of snowcoaches and the number of snowmobiles that were allowed in the park. This understandably created some tension among groups of users that preferred access either by snowcoach or snowmobile. Scientists discerned that groups of snowmobiles had a similar acoustic "footprint" to individual snowcoaches. This created a perceptual shift for park managers: instead of visitation thresholds based on the number of vehicles allowed, managers were able to quantify things in terms of the number of transportation events allowed. Not only did this set the stage for the best possible visitation scenario with the least impact, but it let commercial outfitters make their own decisions about the types of vehicles they wanted to use and how to structure their tours. It also eliminated some of the conflict among user groups: since all OSVs were treated more or less the same, outfitters and visitors didn't feel penalized for choosing one type over the other.

The YNP soundscape monitoring program is one of the longest running environmental acoustic monitoring programs ever. In fact it might surprise you to learn that Old Faithful may be the longest running acoustic data collection site on the planet (that's not an airport)! The winter use monitoring continues to provide the foundation for acoustic monitoring in the ecosystem today. In addition, the monitoring program has collected thousands of hours of sounds representing numerous species and rarely heard events...in a natural laboratory known as YNP. These resources awe visitors from around the world and serve as reference points for future comparisons.

Currently scientists such as Ann Rodman, who coordinates with the Climate Change Response Program in YNP, and Jacob Job, from the Listening Lab at Colorado State University, are exploring how acoustic monitoring in YNP and the region can be used as a tool to address other scientific questions and how acoustic monitoring can be linked with other ongoing vital signs monitoring activities. Specifically, acoustic information will be leveraged to consider what it can tell us, for example about climate change, the timing of important biological events (e.g., phenology), how species composition varies through time and spatial distribution, or how to define the acoustic "signature" of a site. New tools are on the horizon and have the potential to revolutionize how scientists use and interpret acoustic data (Buxon et al. 2018, Mennitt et al. 2012) and how acoustic techniques alone or in combination with other tools can be used as part of a broadscale monitoring framework to measure and monitor ecosystem health (Ross et al. 2018). As one example, YNP is pairing continuous autonomous recorders with climate monitoring stations across an elevational gradient to investigate both the potential and the limitations of acoustic monitoring. This pioneering work will inform how acoustic monitoring can also be used to measure and monitor acoustic variation across YNP and throughout the Greater Yellowstone Ecosystem (GYE) and support soundscape monitoring across other gradients of ecosystem drivers such as land use and human use that are rapidly changing in the GYE. Taken together acoustic monitoring in YNP and across the GYE has already revealed unexpected findings that continue to inform management actions and decision making as well as support opportunities for sharing and interpreting discoveries with park visitors.

Natural sounds are fundamental components of our ecosystems and of YNP—these sounds have a lot to tell us. We just have to listen.

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Want to explore more about Yellowstone's unique acoustic environment? Check out the park's online sound library:
go.nps.gov/yellsounds

or the natural sound archive at Montana State University:
www.acousticatlas.org

For more on the Yellowstone Soundscape Program, visit:
www.nps.gov/yell/learn/management/yellowstone-soundscapes-program.htm

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# Improving Visitor Preparedness and Safety in the Bear Country of Yellowstone National Park

### *by Pat Stephens Williams, Ray Darville, & Sally Vering*

On August 23, 2018, a grizzly mother attacked a 10-year-old boy who was hiking the Divide Trail southeast of Old Faithful. While he was badly injured, his parents prevented the attack from being much worse due to the quick actions and use of bear spray. The bear spray had been rented from a new innovation in the park called Bear Aware, L.L.C., where visitors may rent bear spray and also receive training in the use of bear spray and on bear activity in the park. While bear attacks are relatively rare in Yellowstone, all hikers in Yellowstone are at risk for a bear attack. All visitors, and especially hikers, are encouraged to be prepared for encounters with bears and to be prepared accordingly—meaning maintaining respectful distances and carrying bear spray to use as a deterrent when necessary. On average, bears injure one visitor per year in the park (Gunther and Wyman 2008, Gunther et al. 2015, YNP 2017). In fact, in 2011 and 2015, both considered aberrations, three individuals were killed in the park by bears. With increased visitation and increased bear population, the park, researchers, and Bear Aware are very interested in and studying the visitor behavior related to preparing for potential encounters with the charismatic megafauna of Yellowstone. This study not only gathers non-intrusive information about the visitors, but also looks at the feasibility of expanding the rental approach in the Greater Yellowstone Area as a way to help visitors and wildlife be protected from harm. This study is proposed to be a longitudinal study initiated in 2016. This article summarizes the data collected in 2017.

Bear Aware currently offers bear spray for rent in Yellowstone National Park (YNP) outside Canyon Visitor Education Center. Their services include daily or weekly rental. If a canister was returned unsprayed and undamaged, renters would get their deposit refunded. Visitors could also buy bear spray with no-return expected at competitive prices. Upon completion of their hike(s), renters could return their canisters to one of the following locations: Mammoth, Tower-Roosevelt, Grant Village, Old Faithful, and Madison.

During summer 2017, Bear Aware was stationed at the north end of the Canyon Visitor Education Center opening May 27th and closing in early October. Bear Aware staff answered questions about bears (and other topics), displayed a video on bear safety, and sold their products. During each visit, visitors were asked by Bear Aware staff to answer a few basic questions, including demographic questions, their experience with bear spray, and what they would do if bear spray were not available.

We obtained data from 2,507 groups from May 27 to October 7, 2017. The mean number of groups per day was 18.8 with a minimum of 1 group and a maximum of 58 on two separate days in early July. The number of groups varied by month with the smaller numbers in October (n = 41, 1.6% of cases) and the largest number in July (n = 812, 32.4% of total groups). Almost 80% of cases occurred in June, July, and August. Respondents came from all 50 states and the District of Columbia. The top five states of residence for these respondents were: (1) California (n = 279, 14.3%), (2) Texas (n = 150, 7.7%), (3) New York (n = 102, 5.2%), (4) Illinois (n = 97, 5.0%), and Washington (n = 92, 4.7%). Respondents came from all four regions, more respondents came from the West (n = 558, 28.6%) than any other region. These results also tend to follow the general United States regional populations. A substantial number of respondents came from countries other than the United States. While 78.1% were from the United States, some 19.7% from other countries. Respondents were from 37 different countries, not including the United States. The top five countries in descending order were: Germany, Netherlands, Switzerland, United Kingdom, and France.

Almost three-quarters (74.4%) said they were on their first trip to the park while just over a quarter said this was not their first trip to Yellowstone. They indicated they were expecting to be in the park on their current trip on average for 4.12 days, ranging from 1 day to 18 days. Only about 5% were there for one day only while another 19.9% were there for only two days. Almost two-thirds were expecting to be in the park for four or fewer days. United States respondents were planning to stay slightly longer (M = 4.16 days) compared to international respondents (M = 3.99 days).

We asked individuals to identify how they first learned about bear spray rentals in the park. A total of 2,645 responses were given. The top three sources were: saw kiosk (32.8% of responses), park ranger (16.3% of responses), and park website (6.2% of responses). The Bear Aware website ranked 7th (n = 88, 3.3% of responses); this outcome may be of concern to Bear Aware. However, what we do not know for sure is how many of these respondents accessed the Bear Aware website. In fact, we noted that over a third of respondents saw the kiosk as they were in the Canyon Village area and had no previous information about the Bear Aware services. Looking deeper into this, we found United States visitors were more likely than international visitors to use the following sources: saw kiosk, accessed the Bear Aware website, heard via word of mouth, looked at the park website, and accessed news/TV/radio media. International visitors were more likely to have these sources: park newspaper, *Oh, Ranger* advertisement, and park ranger. United States visitors were more likely to see the kiosk than international visitors while international visitors were more likely than United States visitors to read about Bear Aware in the YNP newspaper, which is distributed at all entrance gates and various other locations.

We asked respondents to indicate if they had carried bear spray on previous hiking trips. Only 6.9% said they had carried bear spray on one or more previous trips. This small percentage suggests these respondents were not accustomed to carrying spray and that their knowledge of bear spray was limited, at best.

Then in one of the most important questions, we also asked respondents to identify what they likely would have done regarding hiking in the park if bear spray rentals were not available. Four answers were provided in this closed-ended question: (1) purchase bear spray, (2) hiked without bear spray, (3) undecided, and (4) would not have hiked. Obviously, the more risky answer would have been "hiked without bear spray." The top answer was purchased bear spray (43.8%), which for the individual user is the costlier option. A quarter (24.7%) would have hiked without bear spray while another fifth (n = 91, 19.1%) said they were undecided about what action they would have taken.

Furthermore, we examined the association between whether the respondent had carried bear spray on a previous hike and what action the individual would have taken if bear spray were not available. This significant, but weak, relationship indicated that those who had carried bear spray before were more likely to purchase the spray for the current trip. Those who had not carried bear spray before were more likely to hike without it, be undecided, or would not have hiked. Moreover, those from the United States were more likely than those from other countries to purchase bear spray or hike without it, while international visitors were more likely to be undecided or would not have hiked without it. There was not a significant relationship between action and region of the United States.

While bear encounters and attacks are relatively rare in the national parks such as Yellowstone, the potential for personal injury and property damage exists for visitors. Bear spray has been demonstrated to be effective in preventing bear attacks for the last two decades, yet many hikers do not carry bear spray, are not trained in how to use bear spray, or do not have bear spray readily available (e.g., in a backpack). Bear Aware is on the front-lines of working with park visitors, helping to prevent these problems and allowing visitors to have more confidence as they hike. Their work enhances and extends the work of park rangers, ranger naturalists, and others. Bear Aware not only exposes visitors to bear spray, but trains visitors in the proper use of bear spray to be more prepared for a bear encounter.

Yet, visitors are diverse as to geographical, cultural, and social backgrounds and may well be unfamiliar of bear behavior and the risks associated with hiking in Yellowstone. Moreover, they may have been ignorant of the importance of carrying bear spray on their hikes. We were encouraged that over 2,500 visitor groups to YNP sought out Bear Aware for information, products, and services and look forward to comparing these data to subsequent years to determine if there is increased awareness and use of bear spray and how to behave in bear country. As a result, there will hopefully be a reduction in negative human/bear interactions.

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# How Have Yellowstone Backpackers Changed?

### *by Ray Darville, Pat Stephens Williams, & Ryan Grisham*

NPS PHOTO - J. FRANK

Yellowstone National Park, comprises 3,472 square miles, is known for its beauty, diversity of flora and fauna, and recreation opportunities (YNP 2016). However, most visitors never go beyond a few steps from the roads and boardwalks in the park. Many visitors appear to be in a hurry and want to see the Yellowstone highlights. Indeed, Yellowstone provides a cornucopia of sights, sounds, and smells. There is much to see from Mammoth Hot Springs to Yellowstone's Canyon, Lamar Valley to Yellowstone Lake, and, of course, Old Faithful, which is the most visited single thermal feature. In these popular park locations, Yellowstone can be quite crowded. In 2016, over four million recreation visits came through Yellowstone's gates (YNP 2017). Since 1990, Yellowstone has averaged over 3.1 million recreation visitors per year and cumulatively some 85 million recreation visits in that period (NPS 2017). No fewer than two million annually have come to Yellowstone since 1975. In addition, about 70% of all recreation visitors are in the park during the three summer months.

While there is much to see and hear in and around these main attractions, there is an entirely different experience available in the 95% of the park that is designated backcountry (YNP

2016). Many backpackers (Oosterhous, et al. 2007) seek the more solitary experience found in Yellowstone's backcountry. Nevertheless, Yellowstone's backcountry is also heavily visited compared to its capacity. Since 1979, over 1.5 million backpackers have registered in the backcountry offices for an overnight trip and since 1993, the number of registered backpackers has varied between 35,000 and 45,000 annually. In 2016, almost 45,000 backcountry campers (backpackers) were in the park with about 34,000 in the park during June, July, and August alone (77% of all backcountry backpackers for the year). Thus not only are there a substantial number of backpackers, but they are concentrated into three summer months.

Yellowstone has approximately 1,000 miles of backcountry trails and about 300 designated campsites. Advanced reservations are permitted for a $25.00 non-refundable fee. YNP charges backpackers a $3 per person per night fee to help support the backcountry through improvement of campsites, trail maintenance, and other management activities. Maximum limits are imposed on the number of people and stock that may occupy a site and the number of nights they may stay at a site.

Because backpackers' experiences are different from those of frontcountry visitors' experiences, this study provides YNP managers insight into this population of visitors. This new study sheds light on not only backpackers themselves, but also on their experiences, their preferences, and their opinions toward Yellowstone backcountry policies and practices. In addition, this study is a follow-up and builds upon the Oosterhous, et al. study conducted in 1999 (2007). The changes in visitors between 1999 and now suggest backcountry managers should re-examine current strategies in planning and management so that backcountry mangers can better optimize backpacker experiences and address backpacker concerns.

Researchers in the Oosterhous et al. (2007) study received survey responses from almost 650 backpackers. Briefly, researchers found backpackers were most likely to be adult, white males, young, not married, and college educated. Visitor trips (defined by Yellowstone Backcountry Trip Planner as "a contiguous itinerary that enters and then exits the backcountry at a trailhead or developed area") lasted a little over two nights with a party size of just more than three. They typically were experienced backpackers, but were relatively inexperienced in Yellowstone's backcountry. Furthermore, the results indicated backpackers assigned higher importance to solitude and tranquility compared to other motivations for the backcountry experience. Moreover, they desired avoiding crowded areas, looking at park scenery, escaping from everyday routine, enjoying adventure, and exploring new territory. In addition, some market segmentation existed based on selected socio-demographic characteristics. For example, women gave a greater importance than men on wildlife observation, exploring new territory, relaxing, feeling in tune with nature, looking at scenery and other aspects of the backcountry experience; whereas, men placed more emphasis than women on the importance of fishing as part of their backcountry experience (Oosterhous et al. 2007 for a full description). Our study is a partial replication of the previous work. While a portion of the present study paralleled the previous work closely for data comparison, changes were made as indicated by current trends in visitors in Yellowstone and the needs of management for future planning in policies and procedures. Oosterhous et al. (2007), for example, focused more attention on the motivations and experiences among backpackers, so we focused on whether significant changes have occurred in this 17-year gap.

## Methods

We conducted a quantitative and qualitative social survey of backpackers in Yellowstone during summer 2016. The survey asked questions about the hiker's trip, their perceptions of crowding, sense of crowdedness, and preferences for the backcountry experience (e.g., directional signs, food poles, pit toilets at campsites, and designated campsites). In addition, as an exploratory technique, we developed a 10-question survey to measure backpackers' knowledge of the backcountry. Park staff reviewed the survey and the Office of Management and Budget approved it as well. Once approval took place, we created the survey instrument in Qualtrics for electronic management and delivery to prospective respondents.

We recognize that our study does not address the many day use hikers who hike throughout Yellowstone on a daily basis. In fact, backpackers represent a relatively small number of overall recreation visitors to YNP. However, our study provides valuable insight into this important recreation segment. Backpackers must register for their trip at any of the nine backcountry offices located in Yellowstone. Our study included backpackers registering at YNP backcountry offices (Bechler Ranger Station, Bridge Bay Ranger Station, Canyon Visitor Center, Grant Village Visitor Center, Mammoth Visitor Center, Old Faithful Ranger Station, South Entrance Ranger Station, Tower Backcountry Office, and West Yellowstone Visitor Information Center) during the study period in 2016. Solicitation occurred between early June and early September. When backpackers came into a backcountry office to register for their trip, a backcountry staff member registered them for their trip and then were supposed to solicit one member of each backcountry group for survey participation; the first backpacker to approach the staff member was the first one solicited. If the first group member declined to participate, a second individual was solicited. Once an individual agreed to participate in the survey, the backpacker completed a short form, which included an email address for contact. After backpackers returned home, we sent them an email concerning the survey, which included the purpose of the study, instructions on how to complete the survey, a statement pertaining the anonymity, researcher contact information, and a Qualtrics hyperlink to the questionnaire. Respondents completed surveys beginning in early September through early November 2016. We sent multiple email reminders to prospective participants. We obtained 670 email addresses. Of those, 71 email addresses bounced, leaving 599 solicited for participation. We obtained 307 useable surveys to be included in the data file for data analysis, yielding a response rate of 51.2%, which is considered acceptable (Babbie 2017). Our sample size was smaller than that of Oosterhous; this may be a reflection of the dynamics of our solicitation process. For example, Oosterhous was working as a backcountry staff member during his summer of data collection and was able to engage backcountry hikers; we did not have this experience. In addition, our lower numbers are consistent with a national trend toward lower response rates for surveys (Babbie 2017). Due to constraints, we were not able to examine sampling bias.

## Results: Demographics

While these backpackers came from 46 states, some 50% of backpackers came from only seven states: Montana, California, Idaho, Colorado, Texas, Washington, and Utah. About 64% were male; 95% were white, non-Hispanic; and about 66% were younger than 40 years old. Furthermore, almost 80% had earned at least a bachelor's degree. Our results are quite consistent with the Oosterhous study, which indicated backpackers primarily came from western states, were young adults, and well educated. One difference was gender. In our results, only 64% were male compared to 71% for the Oosterhous study ($t = -2.345$, $p < 0.01$) Thus, our respondents were slightly more likely to be female compared to the Oosterhous study.

In 2016, group size averaged 3.2 (SD = 2.7) members with a minimum of 1 (11%) to a maximum of 23. Oosterhous' respondents had a mean group size ($M = 3.27$) slightly greater than our group size ($M = 3.21$); the mean difference was not statistically significant ($t = -0.47$, $p = 0.636$). The most prevalent group size was 2 for both studies with just under 50% reporting that group size.

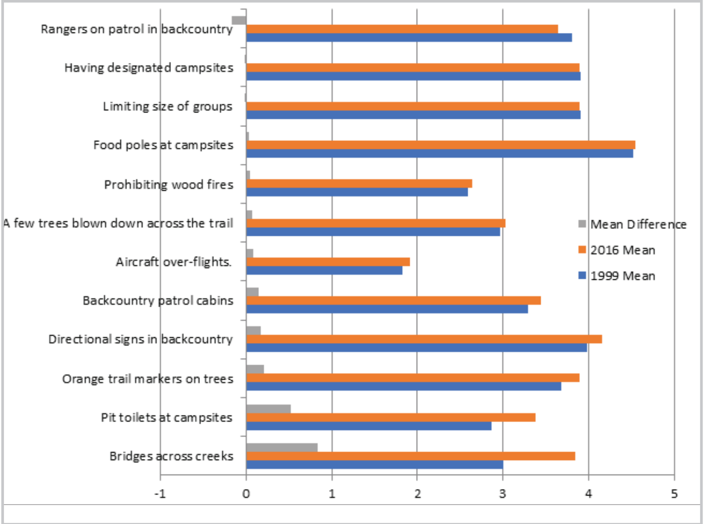

**Figure 1. Changes in the desirability of selected backcountry features.**

In Oosterhous's study, backpackers reported staying an average of 2.29 nights in the backcountry on their trips. In our current study, backpackers averaged 2.62 nights, yielding a mean increase of 0.33 nights. The mean difference was statistically significant ($t = 3.053$, $p < 0.01$). Currently, backpackers are hiking on longer trips compared to 17 years ago. In Oosterhous' study, 83% travelled on foot for at least part of their trip, but in our study 94% travelled on foot; the difference was significant ($t = 8.292$, $p < 0.01$).

## Changes in Desirability of Backcountry Features

Both studies examined backpackers' preferences, or desirability, of selected backcountry features (e.g., bridges over creeks, pit toilets at campsites, orange trail markers on trees, and limiting size of groups). Backpackers were asked to rate their desirability of each feature from very undesirable (1) to very desirable (5). The two studies had 12 common features (table 1) with features listed in descending order of mean differences between the two studies. Five of the 12 did not exhibit significant mean differences between the two surveys: aircraft over-flights (low desirability of mean scores under two), prohibiting wood fires (also toward undesirability), food policies (desirable), limiting group sizes (desirable), and having designated campsites (desirable).

Seven features showed significant mean differences (figure 1). For six of these seven, current backpackers were significantly more likely to desire a feature compared to those participating in the previous study. Current backpackers were significantly more likely to want bridges across creeks ( $p < 0.01$), pit toilets at campsites ( $p < 0.01$), orange trail

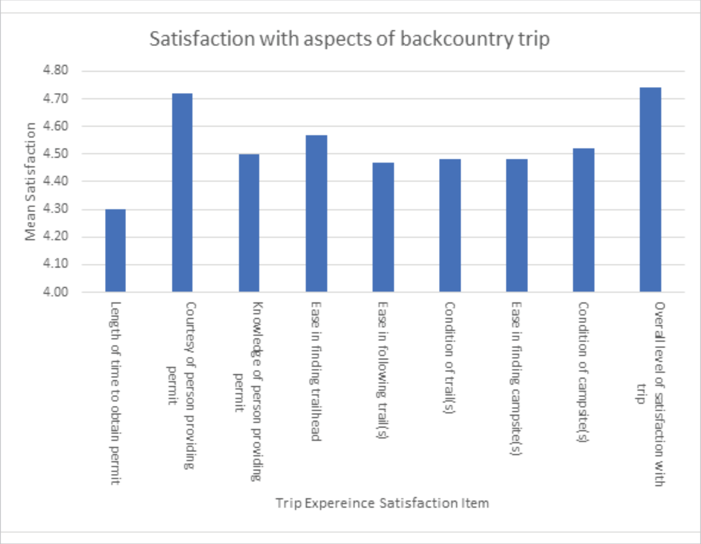

**Figure 2. Satisfaction with aspects of backcountry trip.**

markers on trees ($p < 0.01$), and directional signs ($p < 0.01$). In addition, they were more likely to find a few trees blown down across the trail as desirable compared to those in the Oosterhous study ($p = .049$). Finally, current backpackers (compared to the Oosterhous study) were more likely to desire backcountry patrol cabins ($p = .003$), but were significantly less likely to desire interacting with rangers on patrol ($p = .002$). It is possible these backpackers wanted the cabins for resting locations or for location markers so that they knew where they were on the trail, but they were not necessarily desiring more interaction with rangers, which is consistent with a general desire for backcountry solitude.

## Backcountry Experience

Though backcountry hikes are increasing, current backpackers did not seem to believe crowding was a major problem. Only 3.7% said they experienced either moderately or extremely crowding, while 83% said they were not at all crowded. As a follow-up, we asked their opinion on the number of backcountry trails. Well over 80% said the number of trails was just right, but a substantial number (16.2%) believed there were not enough trails available for backcountry hiking.

Generally, current backpackers were satisfied to very satisfied with their backcountry experience (Figure 2). On a five-point scale from very dissatisfied (1), dissatisfied (2), neither dissatisfied or satisfied (3), satisfied (4), very satisfied (5), all item means were greater than 4 (satisfied). Means ranged from a low of 4.31 (time to obtain their permit) to a high of 4.74 (overall satisfaction).

## Crowding

A sense of crowdedness can have a negative effect on a backcountry trip, especially since a strong motivation for the hiking experience is for solitude (Oosterhous et al. 2007). Though the number of backpackers is increasing, current backpackers clearly believed crowdedness was not a problem. In our study, some 82% said they felt "not at all crowded," while only 3.7% said they experienced moderate or extreme crowdedness. Moreover, they estimated seeing 2.65 groups per day ($SD = 2.114$); some 12% of backpackers said they averaged seeing no other group per day on their trip. The degree of crowdedness was related significantly to estimated number of groups seen per day ($F = 15.117$, $p < 0.01$). Those who indicated "not crowded" averaged seeing about 2.3 groups per day while those saying they felt extremely crowded averaged seeing 7.5 groups per day.

We compared the estimated number of groups seen per day between the two studies and there were almost no differences between the studies. In our study, 92.3% saw five or fewer groups per day. While generally in 2016 backpackers saw their trip as one that was not crowded, they did express a concern over parking at trailheads. One in seven backpackers said they found parking difficult or non-existent around their trailhead. Difficulty with parking varied by area, ranging from 0% at Thorofare to 25.5% at Canyon. The top five problem areas were Canyon, Pelican Valley, Slough Creek, Lamar, and Old Faithful.

## Commercial Outfitters

Several respondents commented that commercially guided groups in the backcountry are diminishing the backcountry experience, including some strong opinions. Almost two-thirds said they believe commercial use was not acceptable. We tested 13 relationships between their opinion and selected factors; the only significant relationship was with education. Individuals with a higher level of education were significantly more likely than those with less education to believe commercial use was not acceptable. Written comments based on respondents' backcountry experiences supported this quantitative outcome. While some comments on commercial use were positive, most were critical of commercial operations. Backpackers wrote comments such as:

> *"The National Parks should not exist for the benefit of private enterprise/businesses. The National Parks belong to the American public. This especially pertains to the backcountry, where people go to experience solitude and to 'get away from' commercialization and the trappings of civilization;" and*

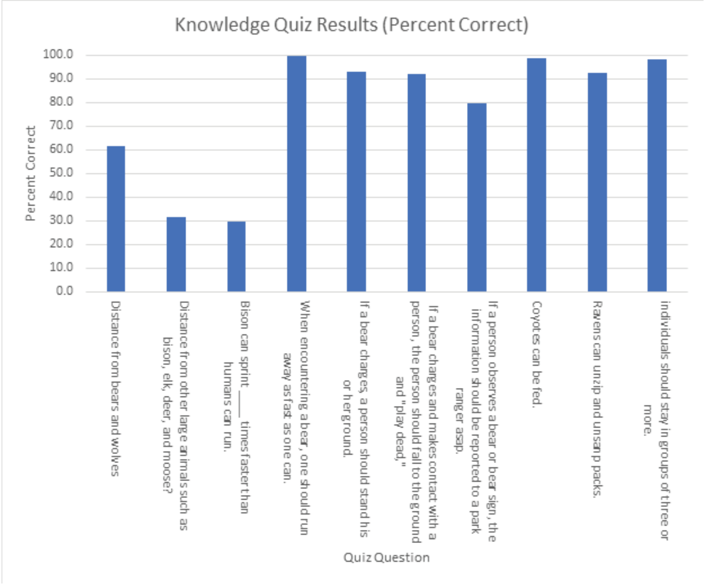

**Figure 3. Scores on knowledge survey.**

> *"Other than the Roosevelt cookout there should not be commercial use because it destroys the integrity of our park. Keep it natural and as simple without crowds as possible. Go to Disneyland if you want commercial."*

## Knowledge

Hiking into Yellowstone's backcountry carries higher safety risks (weather, terrain, and wildlife) than staying on the frontcountry boardwalks. Thus, we wanted to know the level of knowledge of backpackers pertaining to safety in the wild. We gave them a 10-question survey based on information provided by YNP staff to backpackers through the YNP website and in printed materials. Questions pertained to knowledge about bears, bison, coyotes, ravens, and other selected issues; some questions focused on basic backcountry knowledge, while other questions focused on more specific issues such as backcountry safety. We recognize this was a first attempt to quantify backpacker level of knowledge. Given the relatively greater risk to backpackers compared to other park visitors, we believe backcountry users should have appropriate knowledge. While backpackers can gain some of this information through the required backcountry video to be seen during the registration process, we do not see this part of the research as a test of knowledge developed through the video itself or even through the official Yellowstone information for backpackers. Moreover, we simply included this exploratory technique as a way to initially measure backcountry knowledge; however, more research with this approach is needed to develop a stronger sense of backcountry knowledge. Survey scores, using a set of 10 true-false questions, could range from 0 (none correct) to 10 (all 10 correct). Backpackers' scores (figure 3) ranged from a low of 2 (20%) to a high of 10 (100%) with an overall mean of 7.75 (77.5%); some 63% of backpackers scored 8 (80%) or higher on the survey. Backpackers had the highest mean (99.6% correct) on "when encountering a bear, one should run away as fast as one can" and the lowest mean (29.7% correct) on the number of times bison can run faster than humans (the correct answer is three times). We tested selected factors impact to explain survey score differences. None of the results was statistically significant, suggesting backpackers were consistent in their scores across several different socio-demographic and recreation characteristics.

## Backcountry Permit Fee

Yellowstone National Park is now charging a $3.00 per person per night backcountry fee for backpackers and boaters, and a $5.00 per person per night fee for stock parties. Prior to 2015, backcountry permits were free; thus backcountry staff wanted feedback from backpackers on this administrative change. The additional revenue is designated for use to maintain and improve the backcountry and backcountry office visitor services. We asked backpackers if they supported or did not support the new fee and found an overwhelming 93.5% supported the fee. Cross tabulating their opinions by socio-demographic characteristics found no significant differences—support for the fee was nearly universal. Likewise, no significant relationships were observed with trip characteristics. Comments were overwhelmingly supportive, such as: "It's a gift to spend time in the park. worth it!!!" and "What you're doing with the money is positive. You could have an option for people who don't have the money to pay, some volunteer options perhaps, or a scholarship fund," and "If additional revenue is needed to maintain or increase the quality of the experience, I support it," and "fine to charge a little bit. Having good trails is not free. But it needs to be cheap so anybody can go." There were negative comments too, such as "Let nature be free. It's where we all belong. Most of us are broke - it's 2016."

## Conclusions and Recommendations

Our results in some ways are consistent with those of the Oosterhous study and in some ways are different. Our study suggests Yellowstone's backpackers, while a small percentage compared to the total number of annual visitors, are generally satisfied with their backcountry experience. They are more likely to be male, white, non-Hispanic, well educated, and younger, though the study indicates an increase in female backcountry visitors compared to the Oosterhous study.

Backpackers averaged about three members, which is consistent with Yellowstone staff recommendations; however, 11% of respondents said they hiked alone and over 40% hiked in groups of two. These numbers should be of concern to backcountry managers based on safety grounds. In addition, backpackers are staying in the backcountry for a slightly longer period, which may indicate high overall satisfaction with the experience, but it is also possible the increased use will add additional pressure on the existing natural resources.

The requests for increased amenities is an interesting difference to note between the 1999 and 2016 study, especially given the longer trips spent in the backcountry. Backpackers indicated they would like an increased number of bridges, pit toilets, trail markers, and signage. They also wanted to see evidence of backcountry rangers (though they indicated they did not want to see the rangers themselves). This may indicate a trend toward a marked difference in backcountry users in that there are those who want the backcountry experience of designated wilderness "untrammeled by man" (Wilderness Act of 1964) and those who wish to have a slightly less "wild" experience in managed backcountry.

Given the near universal support for the new backcountry fee and considering the current and anticipated future levels of federal government support for parks, park managers should consider other opportunities to allow visitors to support their parks. Yellowstone backpackers might support modest additional fees. In addition, in an effort to increase communication between backcountry staff and backpackers, we recommend backcountry staff inform all visitors how the fee money is being spent; this is good public relations and may encourage further donations once visitors see their money at work.

Continued education of backpackers should continue to be a priority. Our backpackers made a "C" grade on their survey collectively, despite receiving training prior to being issued their backcountry permits. We recommend backcountry managers review the required video and update it as needed. Some backpackers indicated in comments (not presented here) that the video appeared dated and should be re-done to make it more visually appealing and more informative. While this outcome is within expectations, it is also obvious many backpackers need more education, especially concerning wildlife. While knowledge does not prevent all problems in the backcountry, increased knowledge should lead to better trip experiences and reduce the likelihood of problems. Backpackers' experiences may also be improved through policy and practice changes based, in part, on backpackers' preferences and opinions toward backcountry management. For example, a number of backpackers were concerned with pack animals and outfitters as harming the backcountry experience. We hope this study has provided park managers with additional information to continue to make informed decisions for the protection of the resource and enhancement of the visitor experience—the charge of the National Park Service.

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# A DAY IN THE FIELD

## Citizen Science Engagement: A Vital Part of Yellowstone Science

*by Erik Oberg*

**Citizen science volunteers collect insect samples and record phenology data at a Washburn Mountain monitoring site.**

Understanding long-term environmental change and documenting patterns in nature requires rigorous protocols, dedicated observers, and a long-term commitment. Increasingly citizen scientists or volunteers from outside the scientific community are contributing to monitoring programs that are difficult or impossible to carry out (Bonney et al. 2009). There are many examples of citizen-based monitoring programs, but one of the most successful and best recognized is the annual Breeding Bird Survey (BBS; Ziolkowski et al. 2010). Beginning in 1966, BBSs included approximately 600 survey routes east of the Mississippi River. Today citizen scientists complete nearly 3,000 survey routes annually throughout the U.S. and Canada. These efforts help track population trends for over 400 bird species, and the data have contributed to more than 450 scientific publications. Citizen science volunteers at Yellowstone have been conducting BBSs since 1987.

Many decades before the coining of the term "Citizen Science," Yellowstone National Park (YNP) benefitted from volunteer data collection with early park managers relying on visitor creel counts to estimate fish populations. Today, volunteer anglers continue to help characterize native and non-native fish distributions. Between 2002 and 2016, over 900 volunteers logged almost 23,000 hours and sampled 7,000 fish, contributing much to our current understanding of trout genetics. Before the days of tracking collars and digital photos, visitors also turned in thousands of wildlife observation cards, as nothing inspires citizen science volunteers like YNP's big mammals. Throughout the 1990s, park researchers engaged over 600 citizen science volunteers to study coyotes and foxes; other citizen monitoring projects enhanced Yellowstone's ability to collect water samples. These efforts helped shed light on meso-carnivore response to wolf reintroduction and provided useful baseline water quality data to examine watershed responses to changing mammal populations. Another ongoing citizen science campaign in YNP formed following the reintroduction of wolves in 1995. "Wolf Watcher" volunteers arrived to help record pack movements, dynamics, and wolf ecology. Wolf Watchers have helped park managers document a mange

**Carabid beetle, *Poecilus scitulus*, with mite parasites collected near Gardiner, Montana as part of a citizen science Climate Change Monitoring Phenology Project. Only 0.75in. long, this tiny creature is a key indicator species.** NPS PHOTO - A. ZAIDEMAN outbreak, monitor genetic characteristics, and study seasonal variations in predation patterns. These watchers share their passion, knowledge, and spotting scopes with thousands of visitors every year. In 2016 alone, Wolf Watchers contributed over 13,000 hours, delivering public presentations and making visitor contacts in the field.

Despite its rich biodiversity, YNP was set aside for its geysers. It's no surprise that a citizen science program grew around these unique park treasures. Have you ever stood by a geyser and wondered, "When is this thing going to go off?" There is a decent chance a "Geyser Gazer" volunteer, clipboard in hand, was there to provide you an estimate with train-schedule precision. Founded in 1983, the Geyser Observation and Study Association's (GOSA) purpose is the collection and dissemination of information about geysers and other geothermal phenomena in YNP. They gather eruption data on many of the park's most popular thermal features and maintain an online database and timetable for eruptions. Some GOSA data is being incorporated into a park study examining geyser eruption cycles.

Among the most successful citizen scientist opportunities across the National Park Service (NPS) has been the BioBlitz: www.nps.gov/subjects/biodiversity/national-parks-bioblitz.htm. A BioBlitz is an organized event focused on identifying as many species as possible in a specified area, typically over a 24-hour period. BioBlitzes are a partnership between the NPS and National Geographic Society and have introduced many citizens to volunteer science opportunities in the parks. In 2009, approximately 125 scientists, park staff, and volunteers conducted Yellowstone's first BioBlitz and documented over 1,200 species, including the first park records of little seed ricegrass (*Piptatherum micranthum*), a blue lichen (*Aspicilia desertorum*), and a tiger beetle (*Cicidela haemorrhagica*).

As the NPS enters its next century of stewardship, YNP managers recognize novel and emerging threats to park resources—some iconic and some little-known. The park is teaming up with Yellowstone Forever (YF), the park's education and philanthropic partner, to offer hands-on learning opportunities. Trained and accompanied by park biologists, these YF citizen science volunteers will gather baseline data to better understand stressors unique to each species or ecological community. Each of the five projects below was prioritized by park staff and began recruiting new citizen science volunteers in 2018.

A steadily recovering bison population has caused concern as to whether or not there is "home on the range" for the most diverse and abundant ungulate and carnivore community in North America. The YF Home on the Range Project will collect data to evaluate bison, elk, bighorn, mule deer, and pronghorn dietary patterns and nutrition, habitat use, migration patterns, birth rates, survival rates, and population growth rates. Managers and decision makers need new information on how park resources are being affected to guide future management.

**Volunteers Dani Hatfield (foreground) and Maureen Cairns service a pitfall trap to monitor Carabid beetles, an important indicator species. Almost 800 samples were collected in 2018 with citizen science support.**

Phenology is the study of plant and animal life cycle changes over time. By recording these changes, park managers can better anticipate resource protection needs and plan management actions. Volunteers will collect Carabid beetles, a diverse and abundant invertebrate community that represents ecosystem health. ("Insects as a Vital Sign in the Greater Yellowstone Ecosystem," this issue). Volunteers from YF will also participate in a simple monitoring program documenting key phenological events such as green-up, flowering, seed set, and die-off for sentinel plant species. Collected data will be used to fill an important knowledge gap about important phenological events and how they may be changing over time.

Invasive weeds compete with native vegetation for space and resources, lower species diversity, and provide little forage value for wildlife ("Invasive Plants as Indicators of Ecosystem Health," this issue). Given what we know about the current grazing pressures in the park, understanding how much forage is available for wildlife assists in making science-based management decisions. Weeds are an enormous economic drain that negatively impact ecosystem health. Volunteers coordinating with YF will photograph and gather locations for seven high priority invasive plant species. Data will be used to better understand invasive plant ranges, estimate rates of spread, and prioritize invasive plant treatments and native plant restoration locations.

Red-tailed hawks are charismatic, common, and easily recognizable, making them ideal candidates for citizen science monitoring. A red-tailed hawk nest monitoring project in YNP is part of a continental-wide effort to provide baseline data on nesting success and will serve as an important indicator for future change. Yellowstone's northern range offers a unique opportunity to monitor this species in a relatively natural landscape, providing baseline data from which to measure future trends as visitation and climate patterns change. Citizen science volunteers working with YF instructors will monitor breeding behavior and territory use by observing known nest locations.

Pikas are small, non-hibernating members of the rabbit family that typically dwell at high elevation sites. They are vulnerable to a warming climate and tend to abandon lower elevation sites in favor of higher, cooler habitat. Volunteers will assist by conducting surveys at historic pika sites, listening for pika calls, and searching habitat for evidence of recent pika activity.

Plants and animals within YNP are being affected by local, regional, and global stressors. Citizen science efforts will help maintain the park's capacity to monitor important park resources and will contribute to a deeper understanding of their status and trends. These authentic, hands-on volunteer and learning experiences also serve to educate and inspire the next generation of park stewards. To find out how you can become a YNP citizen science volunteer, visit www.yellowstone.org/experience/citizen-science or contact Erik Oberg, erik_oberg@nps.gov.

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**Participants learn field techniques in the first Yellowstone Forever Citizen Science Field Seminar. (**PHOTO - ©L. OSBURN)

**Erik Oberg** is a Yellowstone Biologist with 25 years of National Park Service experience in resource education, water quality monitoring, and biological inventories, with a focus on invertebrates. He has worked in six parks, including Joshua Tree, Sequoia, and the George Washington Memorial Parkway, and has recruited hundreds of citizen science volunteers.

# NEWS & NOTES


NPS PHOTO - J. LAWLER

## New Deputy Chief of Yellowstone Center for Resources

Hillary Robison has joined Yellowstone National Park's team as the new Deputy Chief of the Yellowstone Center for Resources (YCR). For Robison, this is a return to where her career started as a volunteer in the mid-1990s. Hillary earned a dual-degree in History and Integrative Biology from U.C Berkeley and earned her PhD studying grizzly bear conservation issues in the Greater Yellowstone Ecosystem. Thereafter, she worked on habitat research and management issues as the Ecosystems Biologist for the Government of Nunavut in the eastern Canadian Arctic. Hillary later moved to northwest Arctic Alaska to work for the National Park Service (NPS) as the Wildlife Biologist for Western Arctic National Parklands (WEAR), which comprises the 9.7 million acres of Cape Krusenstern National Monument, Kobuk Valley National Park, and Noatak National Preserve.

Most recently Hillary worked as the Chief of Resources for WEAR. While at WEAR, Hillary was the brown bear and muskox vital sign lead for the NPS Arctic Network Inventory & Monitoring Program. Hillary is passionate about the NPS mission and says she "loves working for the NPS because I have the opportunity to work with natural and cultural resource scientists and managers, NPS staff and volunteers, Native Alaskan and Native American tribes, stakeholders, and partners to conserve and protect resources for our generation and those to come."

YCR Chief Jennifer Carpenter noted, "We are so happy to have Hillary back in Yellowstone in a new leadership role. Her background and experience within Yellowstone and her expertise with complex resource management issues will be a great asset to the park."

## Gunther Presented with Director's Natural Resource Award

Some people go above and beyond the call of duty to manage the land, water, air, and artifacts in innovative, creative ways. They set a fine example of using scientific research to make informed management decisions.

On Sept. 19, 2018, the recipients of the Director's Natural and Cultural Resource Awards for 2015, 2016, and 2017 were honored in Washington D.C. Yellowstone bear biologist, Kerry A. Gunther, was presented with the 2017 Natural Resource Management Director's Award for his work with Yellowstone grizzly bears - the goal of which has been to inform conservation of the bear population and thereby facilitate the bears' removal from protection by the Endangered Species Act.

## Geoscience Outreach Project Begins

In 2018, Behnaz Hosseini from the YNP Geology Program received the E-An Zen Fund for Geoscience Outreach Grant from the Geological Society of America to develop a geoscience outreach project in Yellowstone. With the grant, she recently purchased two FLIR C3 thermal infrared (TIR) cameras to help visitors understand the important role that TIR plays in monitoring Yellowstone's hydrothermal areas. While teaching the public about the scientific merits of TIR, the project hopes to reinforce a message of safety in hydrothermal areas.

Behnaz will begin delivering this program in the Upper Geyser Basin, Norris Geyser Basin, and Mammoth Hot Springs this spring, prior to departing for graduate school. Please contact her at (307) 344-2208 or behnaz_hosseini@nps.gov if you would like to get involved with this exciting project!

## MSU Earth Scientist Cathy Whitlock Elected as Member of U.S. National Academy of Sciences

*by Denise Hoepfner, MSU News Service*

A Montana State University professor of Earth sciences whose work over the past four decades has greatly impacted the fields of geology, geography and ecology and advanced our understanding of the processes shaping Yellowstone National Park has been elected by her peer scholars to be a member of a distinguished national organization committed to the advancement of science.

Cathy Whitlock is among the newest members of the U.S. National Academy of Sciences, one of the highest honors a scientist can receive. According to the academy's announcement, published May 1, 2018, members are elected in recognition of their distinguished and continuing achievements in original research, and membership is widely accepted as a mark of excellence in science.

Whitlock is the first scientist from a Montana institution to earn the distinction. She was formally inducted at the 2019 NAS annual meeting in Washington, D.C.

"I am thrilled and honored by my election to the NAS and for the opportunity to represent my discipline at a national level," said Whitlock, a professor in the Department of Earth Sciences in MSU's College of Letters and Science and a fellow of the Montana Institute on Ecosystems.

Over the course of her nearly 40-year career, Whitlock has produced a broad body of groundbreaking research that has led her to national and international recognition for her scholarship and leadership in the field of past climate and environmental change.

She was lead author of the 2017 Montana Climate Assessment, a report released by the Institute on Ecosystems that focuses on climate trends and their consequences for Montana's water, forests and agriculture. The first in a planned series, the assessment is the result of two years of research conducted in collaboration with the Montana Climate Office, Montana Water Center and Montana State University Extension.

Whitlock has published more than 190 peer-reviewed journal articles and book chapters on the topics of vegetation, fire and climate history in leading scientific journals such as the Proceedings of the National Academy of Sciences, Nature, Science, Ecology, PLOS One, and BioScience, among others.

Additionally, she has been recognized for her outstanding contributions with numerous awards and appointments, including her selection as a fellow of the Geological Society of America and of the American Association for the Advancement of Science. In 2014, she received the international E.O. Wilson Biodiversity Technology Pioneer Award, which honors individuals who have made significant contributions to the preservation of biodiversity.

Upon joining the MSU faculty in 2004, Whitlock established the MSU Paleoecology Lab. At MSU, she served as founding director of the Institute on Ecosystems from 2011 to 2017. She is currently the lead investigator on the National Science Foundation Wildfire Partnership in Research and Education (WildFIRE PIRE) project and is the MSU co-investigator for Montana's NSF Experimental Program to Stimulate Competitive Research (EPSCoR RII Track 1) project.

Whitlock said she is grateful for the support she has received at the state's flagship research university, and for the "endless opportunities for research and learning that come with being in Yellowstone's backyard."

"MSU is an exceptionally collaborative home for researchers and I'm grateful for the support that I've received from this university through the years."

"Throughout my career, I've been fortunate to have had inspiring and supportive mentors who encouraged me along the way, dynamic and engaging colleagues who have kept the science interesting and fun, and some of brightest graduate students anywhere," Whitlock said. "Together, we've shared amazing moments of discovery, lots of challenging but unforgettable field experiences, and many moments of laughter."

## Biologists Develop Framework for Prioritizing Yellowstone Cutthroat Trout Conservation Efforts

*by Christie Hendrix*

Given limited funding, logistical constraints, and increased threats to Yellowstone cutthroat trout (YCT), a group of federal, state, and conservation organization biologists collaborated to create a prioritized framework for preserving the species within their historic range. With focus on the Greater Yellowstone Area (GYA), the biologists worked to develop a framework based on data collated by the Multistate Interagency Yellowstone Cutthroat Trout Work Group.

The results of their study were published online in June 2018 in the journal *Fisheries* ("A Portfolio Framework for Prioritizing Conservation Efforts for Yellowstone Cutthroat Trout Populations"). In brief, the framework helps fisheries managers prioritize regions where conservation efforts may have the greatest benefit to YCT.

The biologists determined genetic purity, resiliency, threats from non-native species, and climate change vulnerability were the most important variables to include in their framework. Their results found 70% of YCT populations were either slightly hybridized or occurred in waters with non-native species, demonstrating a significant risk to YCT residing in waters in or adjacent to non-natives. The biologists also found 40% of YCT populations lived in habitats that offered little refuge in the face of changing climate. Notably, even YCT in higher-elevation mountainous areas in Yellowstone National Park are at risk from a changing climate.

Through their study, the authors ranked 36% of existing populations as a high priority for conservation. However, only 14% of current YCT populations were shown to be secure from near-term population threats. The authors hope this framework provides a basis for focused, multi-agency YCT conservation efforts in GYA locations that have high chances of success. The results of the framework may also provide a rationale for securing funding and directing actions that focus on bolstering individual populations and the species as a whole.

## Steamboat Geyser Snaps, Crackles, & Pops

*by Christie Hendrix & Jefferson Hungerford*

Norris Geyser Basin's Steamboat Geyser, home of the world's tallest active geyser, spent much of the last 12 months showing off its eruption skills. While less famous than Yellowstone's Old Faithful Geyser, Steamboat is known for erupting up to 350 feet (91 m) high and has a steam phase that sometimes lasts for days. Witnesses often report that eruptions sound like thunder or a freight train. Steamboat Geyser erupts infrequently and at unexpected intervals. In some years, it erupts only once per year; at other times it goes years without eruptions. March 15, 2019 marked the one-year anniversary of an amazing pulse of activity resulting in 41 eruptions!

These eruptions have been a surprising treat for park visitors and geyser enthusiasts alike. While the activity at Steamboat has generated much public interest, numerous eruptions in a single year are not outside the historic norm. Over a span of four years starting in 1963, Steamboat Geyser erupted 26, 29, 22, and 10 times a year, respectively. And in 1982 and 1983, there were 12 and 23 eruptions, respectively. Since that time, Yellowstone has only seen 20 eruptions in 31 years. Until now…

Scientists are investigating what triggers large numbers of eruptions at Steamboat Geyser in a single year. Park geologists, along with their Yellowstone Volcano Observatory partners, are currently combing through seismic, GPS, temperature, and water discharge data to identify signals that indicate changes in geyser activity.

NPS PHOTO - J. FRANK

NPS PHOTO - J. FOTHERGILL

# New Paper Addresses Potential Strategies for Managing Whitebark Pine in a Changing Climate

### *by Christie Hendrix*

Authors of a recent paper tackled a problem that today's land managers face given projected future climate: how do we best focus efforts to preserve whitebark pine on our lands and where do we start? The paper, "Putting Climate Adaptation on the Map: Developing Spatial Management Strategies for Whitebark Pine in the Greater Yellowstone Ecosystem*" identifies ways that managers can spatially focus their efforts on protecting an iconic species. The authors took a stepwise approach where they first identified projected future climate effects on whitebark pine. Second, they identified possible adaptive management actions that might alleviate some of the effects of climate change. Third, they put together two lists of spatially-explicit management strategies for the Greater Yellowstone Ecosystem (GYE) whitebark pine: one that considered future climate projections ("climate-informed management") and one that did not (the status quo). Finally, they evaluated the differences between how effective these two management strategies were at mitigating impacts to whitebark pine from climate change using the future projections identified in the first step. A key difference between the two strategies is that the GYE's current management accounts for land management policies (e.g., wilderness designations) and where logistical constraints exist (e.g., roadless areas). The climate-informed strategy acts simply on science-based information about the resource and climate change, and does not consider logistics, access, or constraints related to current land management agency policies. The recommended actions are focused in locations where they would be most successful.

By comparing the results of the two strategies, managers can identify both where they might be more successful with their efforts and what type of actions to consider (e.g., thinning, planting, fire use). The climate-informed strategy recommended activities over a wider range than currently being considered. The newly suggested areas and activities allow managers to consider locations that science shows may benefit from actions but may take slightly more effort to implement, such as wilderness areas that would require a more stringent review of actions. With this information, land managers and perhaps even public landowners will have a tool to reevaluate their current strategy for maintaining whitebark pine stands throughout the GYE. National Park Service staff involved in the process were pleased by its outcome, and feel the results should be beneficial to land managers and members of the Greater Yellowstone Interagency Whitebark Pine Subcommittee.

*https://link.springer.com/article/10.1007/s00267-018-1029-2

# Yellowstone Convenes Science Information Sharing Panel on Aquatic Invasive Species

### *by Adam Sepulveda*

Yellowstone National Park (YNP) supports one of the most significant aquatic ecosystems in the U.S. Headwater streams and rivers emerge from the park and join to become three of America's most important waterways and ultimately flow into the Pacific and Atlantic oceans: the Yellowstone River, the Missouri River and the Snake River. At the heart of YNP lies Yellowstone Lake—the largest alpine body of water in North America. The park encompasses about 2.25 million acres, of which 5% is covered by water including more than 220 lakes and 2,650 miles of streams.

A principal threat to Yellowstone's aquatic resources and the natural ecosystems they support are the numerous aquatic invasive species (AIS) advancing across the U.S. At risk is permanent loss of these resources because once AIS are introduced and become established, there is often no way to completely remove them. AIS are often costly to manage, and they can persist and cause irreversible harm. The introduction of certain AIS species could result in complete loss of world-class trout fisheries, closures of waters to public use, and disruption of habitat and natural ecological functions that impacts important birds and mammals. Lake trout in Yellowstone Lake are a prime example of the potential far-reaching ecological and economic damage that can be caused by an aquatic invader.

Effective prevention, early detection, and control of any further introductions of AIS is required to preserve YNP and downstream waters for future generations. However, prevention efforts are challenging since more than four million people annually visit Yellowstone. Waters where boating is allowed are exposed to watercraft from all 50 U.S. states, Mexico, Canada, and occasionally countries outside North America.

To bolster aquatic resource protection efforts, YNP initiated a Science Information Sharing Panel (SISP) comprised of external agency, tribal and university AIS experts. Panel members include Kim Bogenschutz (Iowa State AIS Coordinator), Robyn Draheim (Independent contractor), Erik Hanson (Confederated Salish & Kootenai Tribes, AIS Coordinator), Eric Hellquist (State University of New York Oswego, Aquatic Botany Professor), Chris Jerde (UC Santa Barbara, Aquatic Invasive Species Professor), Adam Sepulveda (US Geological Survey, Aquatic Invasive Species Biologist), and Theresa Thom (Pacific Region, U.S. Fish & Wildlife Service). The SISP met in June 2018 to evaluate the strengths, weaknesses, and gaps of Yellowstone's AIS program and provide feedback to aid future planning for the AIS program. External and independent peer reviews, such as the SISP, are a hallmark of good science and a strong program and provide evidence of accreditation to stakeholders and the public.

The SISP concluded that Yellowstone's AIS program currently has a strong and effective watercraft inspection component and a non-native trout control component. The SISP identified numerous potential improvements to the safety, infrastructure, and communications of the watercraft inspection program that would strengthen prevention efforts and enhance visitor experience. However, a robust and effective AIS program requires additional components, which YNP currently lacks, to prevent, detect, and control AIS introductions and spread. These components include rapid response, risk assessment, monitoring and surveillance, outreach and education, infrastructure, operations, regulations, and permanent funding. Program expansion should also consider efforts to prevent introduction and spread from pathways (e.g., anglers who wade could spread AIS currently found in YNP) other than watercraft. The SISP has provided YNP with a detailed roadmap of how to incrementally grow these additional components of an AIS program without weakening the watercraft inspection and non-native trout control programs. YNP staff recognized and are grateful for the exceptional work and robust, highly implementable recommendations provided by the AIS SISP. Shortly after the panel left the park in June, YNP staff took immediate action to implement many SISP recommendations. The panel's final report, anticipated in Fall 2019, will continue to guide improvements to YNP's AIS program well into the future.

# SNEAK PEEK

## Coming Up in *Yellowstone Science*—The Grasslands & Grazing Issue

*by P. J. White, Roy Renkin, Chris Geremia, & Stefanie D. Wacker*

The grassland and sagebrush-steppe habitats in and near Yellowstone National Park (YNP) have been referred to as America's Serengeti because they support abundant and diverse ungulates and their predators. Thousands of bison and elk, and hundreds of bighorn sheep, deer, and pronghorn migrate seasonally across the landscape where they interact with black bears, coyotes, grizzly bears, and wolves, thereby providing one of the premier places in the world to observe and photograph or film wildlife. However, these habitats also have been a source of controversy since the 1920s due to concerns about too many ungulates removing too much vegetation, compacting soils, and reducing the diversity of plants, especially in the northern region of the park known as the "northern range."

Numbers of bison, elk, and pronghorn in the park were controlled during the 1930s through the late 1960s by shooting and removals, as well as public hunting in surrounding states. Park rangers stopped culling ungulates after 1968 and let numbers fluctuate in response to competition, forage availability, harvests, predation, and weather. Thereafter the abundance of elk increased rapidly, with almost 19,000 counted in northern Yellowstone and nearby areas of Montana during 1988. As their numbers increased, more elk began migrating to lower-elevation valleys outside the park during winter, leading some people to conclude the park was overgrazed with insufficient food for the existing numbers of animals. These changes led to contentious debates and independent assessments by the National Academy of Sciences and other groups about whether elk and other ungulates were overpopulated and irreversibly damaging the landscape through excessive grazing, soil compaction, and related effects.

The recovery of grizzly bears and wolves in the park by the mid-2000s contributed to a substantial decrease in counts of northern Yellowstone elk and, as a result, the debate about overgrazing waned. However, bison counts in northern Yellowstone tripled over the subsequent decade and intense grazing in some areas such as the Lamar Valley rekindled the debate about grazing effects on grasslands. This transition from an elk-dominated system to one with a more equal biomass of elk and bison was unprecedented and, as a result, the effects on grassland and sage-steppe communities were uncertain. Unlike elk and other ungulates, bison are constrained by surrounding states from migrating or dispersing much beyond the boundaries of YNP due to concerns about brucellosis transmission to livestock, competition with cattle for grass, human safety, and property damage. Thus, increasing bison densities and associated increases in the duration grasslands were grazed in the park led to concerns about high grazing intensities on some summer ranges that may not be sustainable over time.

Since 2012, biologists have conducted several monitoring and research efforts to document above-ground grass production, percent consumption by the grazing community, soil nutrient availability, soil organic matter, plant composition, bare ground, and litter at several sites in high-use bison areas. In addition, vegetation ecologists have been quantifying sage-steppe communities in the park to spatially describe the variability in plant community composition and be positioned to detect community changes in abundance, bare soil and litter, percent cover, and other metrics over time. The next issue of *Yellowstone Science* will include a series of feature and short articles describing the results of these efforts, and discussing the historic and current effects of grazing and other factors on grassland production and ecosystem stability.

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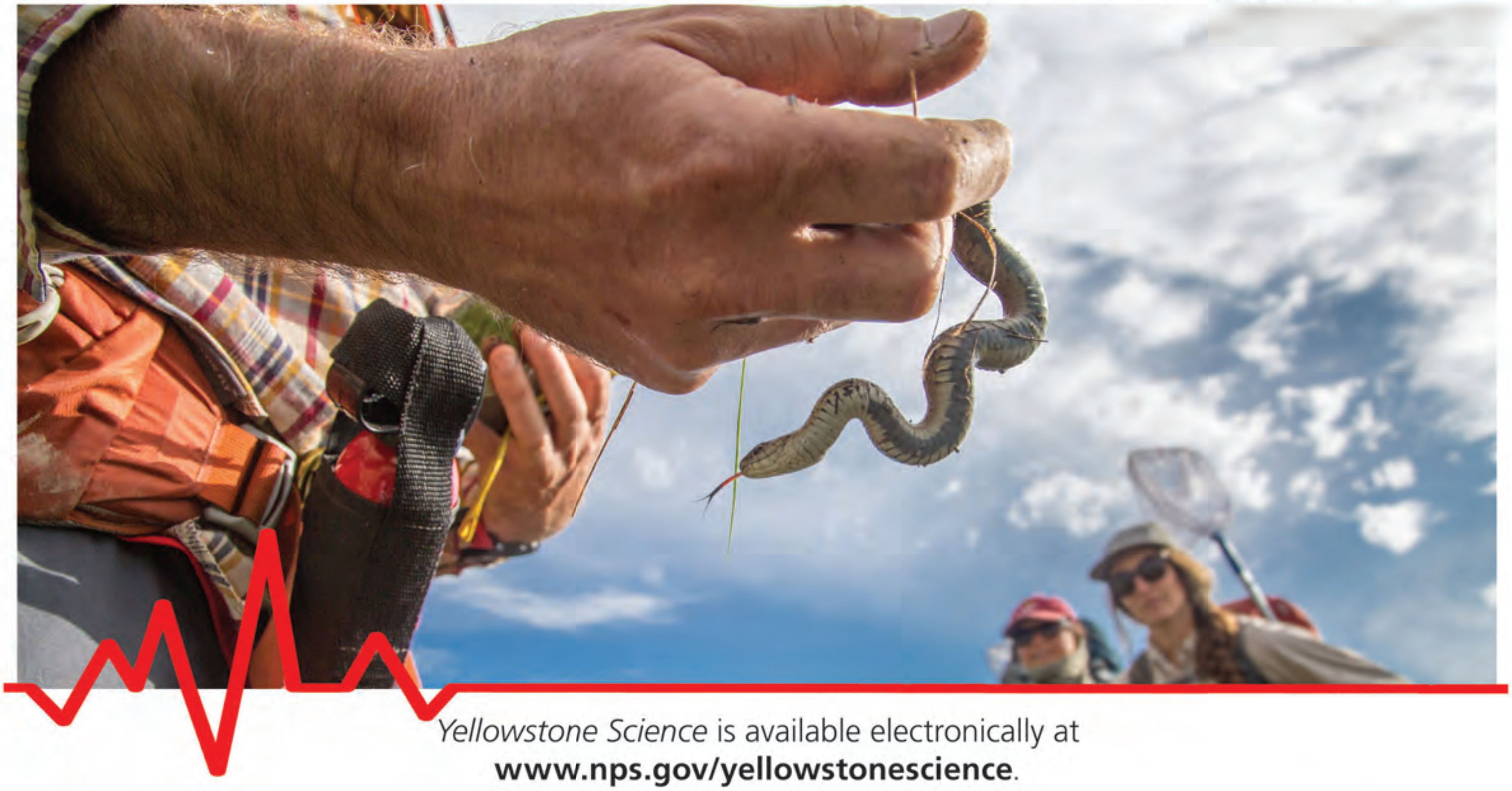
*Yellowstone Science* shares information from scientists and researchers with the public to highlight in-depth, science-based knowledge about the Greater Yellowstone Ecosystem.



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