YELLOWSTONE SCIENCE

SPECIAL ISSUE

Ecological Implications of Climate Change on the Greater Yellowstone Ecosystem

Revisiting Climate Change Predictions from 1992

How Wetlands & Snowpack Help Us Understand a Changing Climate

Water in the Balance

Fear is Not the Answer

The latest comprehensive review of changes to the global climate system states: "Warming of the climate systems is unequivocal, and since the 1950s many of the observed changes are unprecedented from decades to millennia" (from the 5th International Panel on Climate Change report, 2013). Knowing this is true does not necessarily help us understand how these changes are affecting Yellowstone National Park and the surrounding area. It is much more difficult to accurately predict the effects of climate change in a specific location than it is to describe changes to global averages that are happening "somewhere" on the planet. It is even harder to go out on a limb and say how complex natural systems, with all of their fuzzy feedback mechanisms, might react to a changing climate. Yet that is exactly the kind of information we need to help us deal with the uncertainty we are facing in what NPS Director Jon Jarvis has called "the greatest threat we have to the integrity of our natural resources."

How afraid should we be? Twenty-three years ago, in the very first issue of *Yellowstone Science*, Bill Romme and Monica Turner stuck their necks out, before climate change was a popular topic, and predicted three future climate scenarios and the changes that might happen to fire frequency and vegetation. For this special issue on climate change, they graciously offered to revisit their original thoughts, updating them with the benefit of better science and the knowledge they have gained since 1992 through vigorous study in Yellowstone. The evolution of their thinking mirrors the changes that have occurred throughout the scientific community on the topic of climate change.

In 2015, climate change is no longer a vague threat in our future; it is *the* changing reality we live with, and requires continuous planning and adaptation. Temperatures are warmer, snowpack is decreasing, springtime arrives sooner, and the growing season is longer. The authors in this issue describe how these changes have already impacted park resources, and they discuss different possible future climates in which the park is a very different place. Can you imagine Yellowstone without most of the forest that now covers 80% of the park? The certainty of an uncertain future is a difficult concept to embrace, and even harder to plan for, but we are doing ourselves and the next generation a disservice if we defer the discussion any longer.

Fear isn't the answer and our future isn't hopeless. As Romme and Turner state, "Yellowstone is not a static place, but a dynamic, vital, and intact ecosystem…It will not be destroyed, only changed." We still have the power and tools to influence how dramatic that change will be. To succeed, we must care enough to engage in honest discussions, and collectively and individually commit to action. We hope this issue invokes passion and inspires you to get involved. The longer we wait, the fewer options we will have, and the bigger the consequences to the places we care about.

Ann Rodman
Branch Chief, Physical Resources & Climate Science
Yellowstone Center for Resources

Yellowstone Science

a periodical devoted to
natural and cultural resources

volume 23 • issue 1 • March 2015

FEATURES

DEPARTMENTS

Submissions to *Yellowstone Science* are welcomed from investigators conducting formal research in the Greater Yellowstone Area. Article acceptance is based on editorial board review for clarity, completeness, technical and scientific soundness, and relevance to NPS policy.

All photos are NPS unless noted otherwise.

Please visit our website for further information on submitting articles, letters to the editor, viewing back issues, and/or subscription requests: www.nps.gov/yellowstonescience.

Correspondence can also be emailed to yell_science@nps.gov or posted to: Editor, *Yellowstone Science*, PO Box 168, Yellowstone National Park, WY 82190.

YPF YA

Projects funded by our partner organizations, the **Yellowstone Park Foundation** & the **Yellowstone Association**, are noted throughout this issue in recognition of their commitment to scientific research in Yellowstone National Park.

A Climate Change Primer

Ann Rodman

Weather data and climate: Characterizing past climate trends starts with gathering and analyzing a lot of weather data. Over decades, patterns in temperature, rain, and snow emerge that define the climate of an area. The weather in the Greater Yellowstone Ecosystem (GYE) is recorded every day at more than 130 stations (figure 1). These stations tell us a great deal about the current weather and recent trends. Analyzing long-term trends across the entire GYE is difficult because many of these stations were established only recently, in the 1980s and 1990s. The average length of record for stations above 8,000 ft. is less than 30 years, and only six of these stations are located in the alpine zone above 9,500 ft., giving a limited representation of that elevation. Stations with long, consistent records are incredibly important and function as the standard for tracking, describing, and "ground-truthing" trends in the climate record.

Current climate: If a daily or monthly measurement is said to be "above normal" it means, by convention, the measurement exceeds the most recent set of 30-year averages ("normals") calculated by the agencies that run the weather stations (e.g., NOAA, NRCS). Rather than being simple averages, these "normals" are officially published values for each weather station that take into account known sources of bias, such as missing values and changes or disturbance to the equipment. Every 10 years, the time period used to calculate the official "normal" values is updated. Continuously updating the reference period to the most recent 30 years made sense when climate data were used primarily for short-term forecasting and agricultural applications because the goal was to compare the current year to what most people had experienced recently and were "used to." In contrast, in the new era of anthropogenic climate change, it often makes sense to choose an older, historic reference period. As global temperatures increase and snowpack decreases, a continuously changing set of reference averages will unintentionally obscure the long-term magnitude of change. Because of this, scientists sometimes choose a different reference period than the current "normal" when they compare conditions from the past to current conditions. It is important for readers to be aware of this subtle, but important, difference in reference conditions.

Gridded climate data: In order to consistently compare historic climate trends from one part of the GYE to another, there is a need to estimate weather data in places and during time periods not covered by weather stations, and also to fill in data gaps in the existing records. The models that produce these data use a combination of existing and corrected weather records, lapse rates based on elevation, knowledge of local climate anomalies, and satellite data to estimate temperature and precipitation values. These interpolated data are often called "gridded climate data" because daily or monthly weather values are calculated for every square in a regular grid pattern and analyzed to define the climate over time. The three most commonly used data sets are PRISM, DAYMET, and TopoWx. As useful as

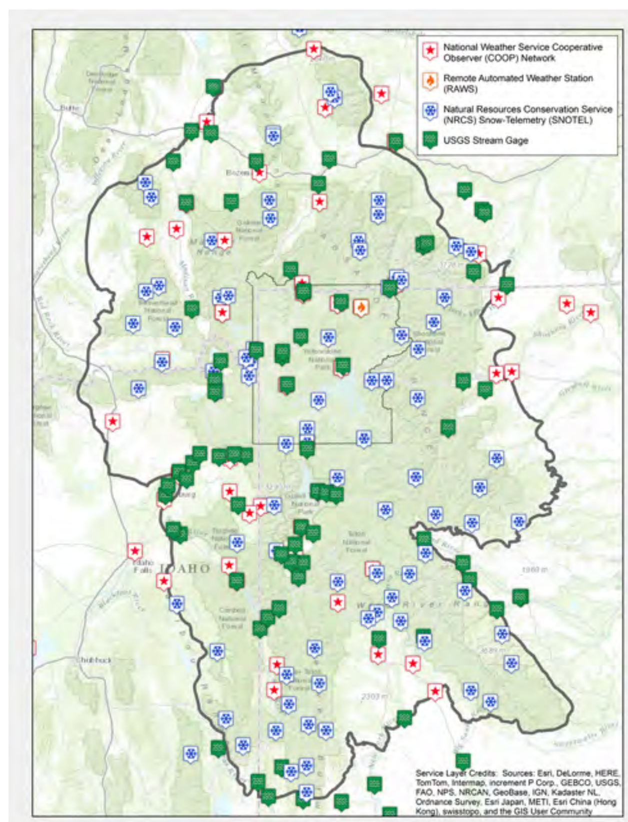


Figure 1. Weather station locations in the Greater Yellowstone Ecosystem.

these data sets are, it is important to remember that they are modeled data–approximations or best estimates, not real, measured values. Ultimately, our confidence in a reported trend will increase as different people, using different data types and analysis techniques, reach the same conclusions.

Role of the Intergovernmental Panel on Climate Change: In 1988, when most people in the Yellowstone area were focused on wildfires, the United Nations was in deep discussion about the human interference with the climate system. To address these concerns, they established the Intergovernmental Panel on Climate Change (IPCC). The IPCC is tasked with coordinating thousands of scientists from all over the world to examine, integrate, and interpret information about the risk of human-induced climate change, its potential impacts, and options for adaptation and mitigation. The IPCC produces regular reports defining the current state of knowledge about human-influenced climate change. As part of this update, they re-evaluate future climate predictions and refine the methods of predicting the type and volume of greenhouse gasses (GHG) that humans will add to the atmosphere between now and 2100.

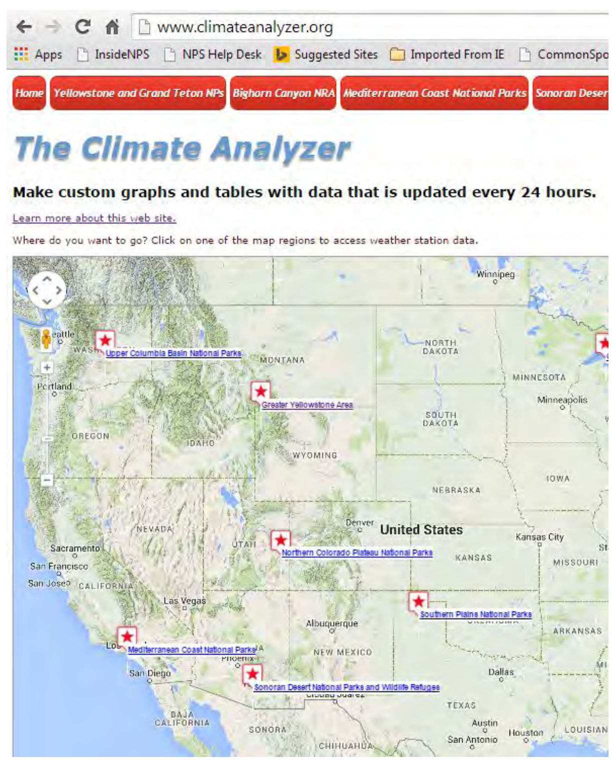
Future climate predictions: The complexity of the global climate system means that there is not one best model for predicting the future climate everywhere on the earth. Instead, scientists use a group of different models that are all good at predicting some part of the answer. Usually, the greatest differences among models are not caused by the mathematical methods used to model the climate system. Most of the uncertainty surrounding the IPCC predictions is due to the fact that it is difficult to predict what people will do. If climate scientists knew what choices humans were going to make about limiting GHG emissions, then their predictions about climate change would be much more certain. The 5th Assessment Report, released in 2014, uses four categories of Representative Concentration Pathways (RCP) to model various future climate scenarios. Each pathway describes the trajectory of GHG concentrations in the atmosphere between now and 2100, and makes assumptions about when GHG emissions will peak. RCP 2.6 is the most optimistic pathway, requiring emissions to decline substantially within the next decade. RCP 8.5 assumes that emissions continue to rise throughout the 21st century without peaking or stabilizing. This pathway, unfortunately, is the one we are currently on.

Although there is some variation in the end result of climate change projections used by the IPCC, there is no doubt that the planet's climate is being altered by human activities. The math and physics involved in climate change research are indisputable. Sea level rises, increasing temperatures, extreme weather events, and declining snow and ice are occurring now and will continue into the future. The extent and intensity of these results may vary by greenhouse gas emission scenarios, but the trajectory of outcomes is clear. Humans will need to adapt, as will wildlife and ecosystems.

Climate change is generally not an easy or pleasant conversation piece. However, it is a conversation that we need to have, and a process we must continue to study. The articles in this issue of *Yellowstone Science* present a snapshot of our current knowledge and understanding of climate change in one ecosystem. Through better understanding, we may arrive at more informed decisions to help conserve and adapt to our changing environment.

YS

Ann Rodman is Branch Chief for Physical Resources & Climate Science at Yellowstone National Park, Wyoming.



The Climate Analyzer is an online portal for climate data in the Greater Yellowstone Area. Information from weather stations and stream gages is available and updated regularly.

www.ClimateAnalyzer.org

Ecological Implications of Climate Change in Yellowstone: Moving into Uncharted Territory?

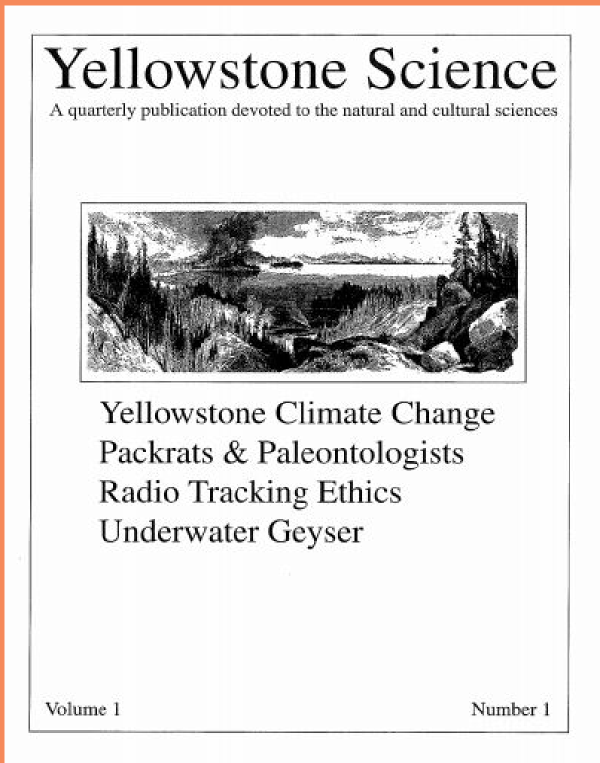
Dr. William H. Romme & Dr. Monica G. Turner

Climate science and understanding how climate change may affect the Greater Yellowstone Ecosystem (GYE) have come a long way since our 1992 *Yellowstone Science* article (Romme and Turner 1992, based on Romme and Turner 1991). In 1992, the potential for global warming driven by anthropogenic emissions of atmospheric greenhouse gases (GHG) was hypothesized but not yet demonstrated. Global climate models were in their infancy, and evidence of climate trends was beginning to emerge. In 1992, ecologists had no quantitative predictions of climate change that could be used to anticipate ecological responses. In our earlier article, we explored logical consequences of qualitative scenarios of climate warming that differed in whether warming was accompanied by drier, intermediate, or wetter conditions.

Today, there is no question that Earth's climate has warmed. This warming can only be explained by accounting for human-caused emissions of greenhouse gases, especially carbon dioxide. Warming will continue throughout the 21st century, even if GHG emissions are reduced. Today, ecologists can access a suite of global climate models that incorporate a state-of-the-art understanding of Earth's climate to explore a range of plausible future climate conditions at relatively fine spatial and temporal scales. A rapidly growing library of field studies provide an understanding of how plants, animals, ecosystems, and even whole landscapes respond to climate change and to climate-driven changes in disturbances, such as fire. Consequently, we are now in a much better position to think about how the GYE is likely to change in the coming century.

Our 1992 article emphasized that the understanding of climate change was still too rudimentary to permit confident predictions about the future. To some extent, that remains true today, but the level of confidence in current trends and ecological responses has greatly increased. Many of the qualitative projections we made in 1992 are still applicable today. For example, we suggested that high-elevation ecosystems, such as whitebark pine forests and alpine meadows, would be especially vulnerable to warming temperatures; that upper and lower tree lines would shift upward with warming; that species with short, rapid life histories would track shifting climate zones more quickly than long-lived species with poor dispersal capabilities; that some forest types, such as Douglas-fir, might expand their range; that fire regimes would be especially sensitive to warming; and that increased fire activity would result in younger forest ages. We also suggested plant communities might appear stable for a long time because mature individuals of some species may persist even as the climate becomes unsuitable for survival of their offspring, but communities could shift very quickly following a disturbance. These qualitative projections still hold today, but they were very general (perhaps even vague) back in 1992. The projections also lacked any timeframe for when changes might occur, which made them seem relevant for the distant future rather than the near term. Today, a better understanding of climate change allows for more specific and more nuanced projections. More importantly, the magnitude and timing of projected climate change has heightened the urgency of anticipating and adapting to such change (Marris 2011).

A first step in thinking about the future is to see what lessons we can learn from past episodes of climate change. Fortunately, several paleoecological studies conducted since our original article was published provide new insights into past climate change and its ecological consequences in the GYE. During the transition from glacial to Holocene conditions (ca. 14,000-9,000 years ago), temperatures rose at least 9-12°F and new plant communities formed as species expanded from their Pleistocene ranges into newly available habitats (Gugger and Sugita 2010,


Yellowstone Science
A quarterly publication devoted to the natural and cultural sciences
Yellowstone Climate Change
Packrats & Paleontologists
Radio Tracking Ethics
Underwater Geyser
Volume 1 Number 1

In the fall of 1992, *Yellowstone Science*, Volume 1 was published and the lead article was titled, "Global Climate Change in the Greater Yellowstone Ecosystem: How Will We Fare in the Greenhouse Century?" written by William H. Romme and Monica G. Turner.

We are pleased to publish their current observations on a subject that is much more familiar to Yellowstone and to most of the citizens of our planet. For a complete transcript of the 1992 article , please visit:

go.nps.gov/climatechange1992

Shuman 2012, Whitlock and Bartlein 1993). Climate variation of a lesser magnitude occurred throughout the Holocene, and was associated with smaller shifts in species distributions and in fire frequency, with more fire occurring during hotter and drier periods (Higuera et al. 2011, Meyer and Pierce 2003, Millspaugh et al. 2004,Whitlock et al. 2008). From this understanding, if future climate change is of similar magnitude to the changes that occurred in the past 9,000 years, then Yellowstone's ecosystems will change, but not to any great degree. However, if the magnitude of future change is comparable to that of the glacial to Holocene transition, then enormous changes are possible—even likely.

Climate Projections for the Mid-21st Century

Advances in climate science now provide far more rigorous and quantitative estimates of the direction and magnitude of climate change during the next half-century than were available 20 years ago. Temperatures in Wyoming and the Northern Rocky Mountains (including the GYE) have warmed over the past few decades, especially at middle elevations (Shuman 2012, Westerling et al. 2006). This warming is associated with earlier spring snowmelt, warmer summer conditions, and a longer growing season and fire season. Climate models predict this warming trend will continue, with average spring and summer temperatures in the Northern Rockies becoming 8-10°F greater by the end of the 21st century (Westerling et al. 2011). This range of predicted temperature increase reflects the differences in how various climate models are formulated, as well as what, if anything, is done by society to reduce global GHG emissions. Even if emissions are reduced dramatically and soon, the GHG already added to the atmosphere will cause a measurable increase in the average global temperature; and the increase will persist beyond the end of the century. It is sobering to realize if little or nothing is done to reduce GHG emissions, the magnitude of temperature increase over the course of the current century could well be approaching the range of temperature change that occurred at the glacial to Holocene transition—implying a potential for major ecological change. The current warming trend is also taking place faster than the one at the end of the Pleistocene; and in a world affected by many human impacts, this could further complicate ecological responses to the changing climate.

Future precipitation remains an important uncertainty in climate projections, so we cannot say whether precipitation is likely to increase or decrease in the GYE. Recent trends in the observed (actual) climate indicate an overriding effect of temperature that exacerbates drought during the growing (and fire) season. Therefore, a warmer, drier future for the GYE appears likely, at least for the coming decades. Average spring and summer temperatures are expected to rise 3.5-5.5°F above the 1950-1990 average by the mid-21st century (Westerling et al. 2011). Hot, dry summers as in 1988 are expected to occur with increasing frequency throughout the 21st century and will become the norm by the latter part of the century. Such climate conditions would be similar to current conditions in the southwestern U.S. and outside the conditions that have been documented in the GYE for most of the past 10,000 years.

Fire Regimes in the Mid-21st Century

The implications of a warming climate for the natural fire regime are much greater than we ever anticipated in 1992. In our early modeling studies, we and our students and collaborators explored a wide range of scenarios that included what we regarded as substantial changes in the fire regime and/or warming temperatures (e.g., Gardner et al. 1999, Hargrove et al. 2000, Schoennagel et al. 2003, Smithwick et al. 2009). In all cases, results pointed to some changes in Yellowstone's forests, but no dramatic shift. The initial take-home message of our studies of the 1988 Yellowstone fires was "resilience"; we did not expect climate change to fundamentally alter the Yellowstone landscape. However, contemporary climate predictions have challenged that assumption. We now think it is possible for fundamental changes to be observed in key processes, such as fire, during this century.

Recent studies revealed a strong positive association between summer temperatures and large western forest fires during the past quarter-century (e.g., Westerling et al. 2006). One of the important mechanisms underlying this relationship involves earlier spring snowmelt, later fall snow cover, and consequently a longer fire season during warmer years. When this statistical relationship is applied to projected future temperatures, the result is more burning in coming decades. For example, Peterson and Littell (2014) projected a 600% increase in median burn area for the GYE and the Southern Rocky Mountain region with only a 2°F rise in temperature. Recognizing spring and summer temperatures in the GYE are likely to raise 3.5-5.5°F by the mid-21st century, Westerling et al. (2011) projected an even greater increase in burning. Summers conducive to widespread burning, like 1988, would become common; and years without any large fires, which are historically frequent, would become rare. What does all of this mean for GYE vegetation?

Vegetation Patterns, Fire Behavior, & Carbon Storage in the Mid-21st Century

The implications of such profound changes in climate and fire regime for the vegetation of the GYE are potentially enormous. However, our understanding of the ecological processes affected by these changes is too rudimentary at present to make any confident predictions. Instead, we offer a few preliminary thoughts—speculations really.

If summers like 1988 become the norm and weather conditions permit large fires yearly, the fundamental controls on the natural fire regime would change. For the past 10,000 years, fire frequency and size have been controlled primarily by weather conditions; most summers have been too wet for lightning ignitions to spread over large areas. During the long decades or centuries between successive fires, forest stands developed dense canopies and heavy fuel structures, which contributed to intense fire behavior when the next fire eventually came—as we saw in 1988. However, as future fires become more frequent, the dense forests and heavy fuels that now characterize much of the GYE would not be sustainable because there would not be time between fires for dense forest structure to re-develop. Younger stands would increasingly dominate the landscape and many GYE stands might resemble open woodlands rather than dense forests. Fire spread and intensity could begin to be limited not by weather but by fuel availability—more like historical fire regimes in dry pine forests of the Southwest. Even though we will likely see more fires in the future, they may not be as intense or as difficult to control as were the 1988 fires. We emphasize, however, our crystal ball is very murky in this regard.

We touched briefly on potential changes in plant productivity in our 1992 article. Warming temperatures may increase forest productivity (Smithwick et al. 2009), assuming water is not limiting—so increased tree production is likely to occur at mid- to higher elevations. Water limitation would likely be observed first at lower elevations and on more southerly aspects. Even if plant productivity increases, the frequent fires expected this century could reduce overall carbon storage in the GYE landscape. Modeling experiments indicate at least 95 years is required for lodgepole pine stands to recover the carbon lost in the 1988 fires (Smithwick et al. 2009); stands with low post-fire tree density would require even longer. Thus, the Yellowstone landscape could potentially transition from a carbon sink to a carbon source in the global carbon cycle (Kashian et al. 2006).

In addition to changes in forest structure, we could see changes in tree species distribution. Researchers have attempted to project the future distribution of western tree species by mapping a species' current range and then characterizing the climatic conditions existing throughout that range (Iverson and McKenzie 2013). Climate models are used to identify specific locations where those conditions are expected to be in the future (see **forest.moscowfsl.wsu.edu/climate** for maps of current and projected future distributions). These projections suggest the ranges of most tree species will shift upward as the lower-elevation portions of their current range become too hot and dry, and elevations above their current range become suitable (figure 1). Mature trees may persist long-term even as the local climate deteriorates, but after fires, seedlings of the previously dominant species will be unable to become established in the new climate. It is even possible new tree species will become more abundant in the GYE. For example, ponderosa pine is found today only on the fringes of the GYE, but could be widespread in a future warmer, drier climate.

Species Distribution Shift: the Case of Aspen

A distribution shift of an important GYE species may already be underway. We did not discuss aspen in 1992, in part because the surprising response of aspen to the 1988 fires had not yet been documented. Prior to 1988, it was thought aspen in the Rocky Mountains regenerated almost entirely via vegetative root sprouting; aspen seedlings had rarely been observed in the field. However, aspen seedlings were observed in 1988 burn areas, including areas where aspen had not been present before the fires, often many kilometers from pre-fire aspen stands (Turner et al. 2003a, b). It seems the sexual reproduction of aspen in the Rocky Mountains occurs primarily after large severe fires (Romme et al. 1997). Aspen seedlings have persisted in many areas, and grow best at higher elevations—in some places higher than the pre-1988 range of aspen in Yellowstone (Romme et al. 2005). Similar patterns are found after fires in the Canadian Rockies (Landhäusser 2010). Meanwhile, aspen forests at the lowest elevations and on the driest sites declined throughout much of the western U.S. in response to severe drought in the early 2000s (Worrall et al. 2010). Research is ongoing to fully understand the processes at work, but the pattern is consistent with expectations of shifts in species ranges from a warming climate (figure 2).

Ecological Interactions

One reason why projections of future conditions are difficult is because ecological processes do not operate in isolation—climate does not act alone, nor do ecosystems experience single disturbances. Interactions among climate, disturbances, biological, and geological processes must be part of the equation.

Figure 1. On the left is a stand of Douglas-fir, now growing at warmer, lower elevations in the GYE. Douglas-fir potentially could move onto the broad, higher, cooler Yellowstone Plateau as the climate warms—if it can tolerate the Plateau's infertile soils—thereby increasing the extent of its range (photo by W.H. Romme, 2013). On the right, subalpine forests of Engelmann spruce, subalpine fir, and whitebark pine may not be able to persist at this current location, which is near the lower edge of the subalpine zone. Their seedlings may begin to establish on higher mountain slopes where climatic conditions remain suitably cool and moist. However, because there is less land area at higher elevations and much of that terrain is bare rock and cliff, the future extent of their range in the GYE will be less than today (photo by W.H. Romme, 2006).

Figure 2. The distribution of aspen in Yellowstone National Park may already be shifting elevations in response to ongoing climate change. On the left are dying aspen stems within an ungulate-proof exclosure near lower timberline on the northern winter range (photo by W.H. Romme, 2010). On the right is a vigorous new aspen sapling germinated from seed after the 1988 fires; this individual and several others in the vicinity are growing at an elevation near or above the pre-fire distribution of aspen in the park (photo by M.G. Turner, 2007).

An interaction that has received much attention is the relationship between bark beetles and fires: two major forest disturbances that increase with warmer temperatures and drought. As beetle outbreaks created swaths of dead trees across Rocky Mountain forests, people assumed devastating fires would soon follow because of the fuel created by beetle-caused mortality. However, detailed field measurements of fuels revealed a different picture (Donato et al. 2013, Simard et al. 2011). The total amount of fuel had not increased; rather live fuels in the form of canopy foliage had been converted to dead fuels which were falling onto the forest floor. Simulations of potential fire behavior within that new fuel bed indicated the likelihood of intense, fast-moving crown fires actually was reduced in the GYE after the beetles because of reduced canopy fuel load; the additional dead fuel on the forest floor might increase surface fire intensity, but only slightly because that material decomposes relatively rapidly (Simard et al. 2011, 2012). Other studies focused on fires that had occurred in recently beetle-affected landscapes by overlaying maps of pre-fire beetle activity onto maps of the fire perimeter and fire severity. One analysis indicated forests in Yellowstone Park affected by a mountain pine beetle outbreak 15 years earlier were 11% more likely to burn in 1988, but that an outbreak 5 years earlier had no influence on the likelihood of burning (Lynch et al. 2006). Analyses of other recent fires in a variety of Rocky Mountain forests have revealed little or no relationship between fire occurrence or severity and previous beetle activity (Harvey et al. 2013, 2014, Kulakowski and Veblen 2007). The overall conclusion is bark beetle outbreaks have had minimal impacts on subsequent fire behavior in higher-elevation forests; weather conditions at the time of the fire (temperature, fuel moisture, and wind) are the overriding control on fire behavior in these ecosystems.

As both of these climate-driven disturbance processes intensify in coming decades, we will likely see a different kind of interaction between bark beetles and fires. A recent study in Douglas-fir forests of the GYE revealed diminished tree regeneration after a severe wind-driven crown fire in places where bark beetles had killed most of the cone-bearing canopy trees 4-13 years previously, leaving the area deficient of seeds (Harvey et al. 2013). Research is underway to determine the importance of this kind of compound disturbance interaction on postfire forest regeneration in other forest types in the GYE; it could lead to reduced forest cover in many places in coming decades.

Research, Monitoring and Education Needs

The need to design creative, long-term monitoring programs sensitive to indications of ecological change is more important now than ever before. We emphasized this in 1992 and suggested measurements of tree establishment and mortality at upper and lower tree lines, status of species near their limits of tolerance, natural disturbance frequency, size and severity, postfire succession, and vegetation-climate-herbivore interactions as high-priority needs. These topics are no less important today, but additional concerns have arisen in the past 20 years. We now recognize the need to understand how changing landscape mosaics will influence the future delivery of ecosystem services, such as natural hazard regulation and carbon storage (Turner et al. 2013). We also need to understand the mechanisms and early warning signs of major qualitative changes in the landscape. For instance, forests could be converted to shrublands or grasslands after fire, if fire intervals become so short trees cannot reach reproductive age before the next fire occurs or if the climate becomes unsuitable for survival of post-fire tree seedlings. The importance of long-term study cannot be overemphasized. The long-term study of the ecological consequences of the 1988 Yellowstone fires produced a tremendous amount of new knowledge (Turner 2010, Romme et al. 2011) which now are the benchmarks to compare the consequences of future fires.

The findings of research and monitoring need to be relayed to the public and to policy-makers as well. In 1992, we said nothing about education and interpretation; but continued educational outreach to park visitors and to the broader public is critical as we all adapt to a changing world. An informed public is one of the best safeguards of special places like Yellowstone, which holds a warm spot in the hearts of many Americans. What we learn from research and monitoring in Yellowstone will be applicable to much of the rest of the Rocky Mountain region and the world.

The Uncharted Future

We have seen some fundamental changes in our thinking since the 1992 paper, as the details of climate change and its impacts have become clearer. Climate warming is inevitable and the changes are coming much sooner than previously thought; many are already underway. It is also apparent that the ecological effects of climate change will be more dramatic and far-reaching than we realized. The Yellowstone ecosystem now appears less resilient to future change than we thought in 1992. We need to be alert to tipping points and thresholds beyond which major qualitative changes will take place. The past may not predict the future, but we may be heading outside the range of climatic and ecological conditions that have characterized the last 10,000 years—moving into uncharted territory.

Despite the big changes that now seem imminent, the future is not necessarily bleak. Yellowstone will continue to evolve as environmental conditions change, just as it did at the end of the Pleistocene and throughout the Holocene. Yellowstone is not a static place, but a dynamic, vital, and intact ecosystem. It will not be "destroyed," only changed. Native plants and animals will still be present, including the charismatic elk and bison, even though relative abundances may change and new species will come onto the scene. Vistas, big and small, will still be breathtakingly beautiful. Yellowstone will also become increasingly valuable for its role in allowing processes and changes to play out with minimal intervention, providing a benchmark for understanding how natural systems change and adapt. Moreover, because so much of the western landscape has been altered by human land use, the GYE, with its large area of contiguous and diverse natural habitats, will be crucial for sustaining a wide variety of species that cannot persist elsewhere. Facing the future does seem daunting given the rapid changes we anticipate; but at the end of this century, we expect visitors to Yellowstone will still experience wonder at Nature's workings and will hold a deep appreciation for all who have worked to ensure the understanding and preservation of this special place.

Literature Cited

Donato, D.C., B.J. Harvey, W.H. Romme, M. Simard, and M.G. Turner. 2013. Bark beetle effects on fuel profiles across a range of stand structures in Douglas-fir forests of Greater Yellowstone. Ecological Applications 23(1):3-20.

Gardner, R.H., W.H. Romme, and M.G. Turner. 1999. Predicting forest fire effects at landscape scales. Pages 163-185 in D.J. Mladenoff and W.L. Baker, editors. Spatial modeling of forest landscape change: Approaches and applications. Cambridge University Press, New York, New York, USA.

Gugger, P.F. and S. Sugita. 2010. Glacial populations and postglacial migration of Douglas-fir based on fossil pollen and macrofossil evidence. Quaternary Science Reviews 29:2052-2070.

Hargrove, W.W., R.H. Gardner, M.G. Turner, W.H. Romme, and D.G. Despain. 2000. Simulating fire patterns in heterogeneous landscapes. Ecological Modelling 135:243-263.

Harvey, B.J., D.C. Donato, W.H. Romme, and M.G. Turner. 2013. Influence of recent bark beetle outbreak on fire severity and postfire tree regeneration in montane Douglas-fir forests. Ecology 94(1):2475-2486.

Harvey, B. J., D.C. Donato, W.H. Romme, and M.G. Turner. 2014. Fire severity and tree regeneration following bark beetle outbreaks: The role of outbreak stage and burning conditions. Ecological Applications 24:1608-1625.

Higuera P.E., C. Whitlock, and J.A. Gage. 2011. Linking tree-ring and sediment-charcoal records to reconstruct fire occurrence and area burned in subalpine forests of Yellowstone National Park, USA. The Holocene 21(2): 327-341.

Iverson, L.R., and D. McKenzie.2013. Tree-species range shifts in a changing climate: Detecting, modeling, assisting. Landscape Ecology 28(5):879-889.

Kashian, D.M., W.H. Romme, D.B. Tinker, M.G. Turner, and M.G. Ryan. 2006. Carbon storage on landscapes with stand-replacing fires. BioScience 56(7):598-606.

Kulakowski, D., and T.T. Veblen. 2007. Effects of prior disturbances on the extent and severity of wildfire in Colorado subalpine forests. Ecology 88(3):759-769.

Landhäusser, S.M., D. Deshaies, and V.J. Lieffers. 2010. Disturbance facilitates rapid range expansion of aspen into higher elevations of the Rocky Mountains under a warming climate. Journal of Biogeography 37(1):68-76.

Lynch, H.J., R.A. Renkin, R.L. Crabtree, and P.R. Moorcroft. 2006. The influence of previous mountain pine beetle *(Dendroctonus ponderosae)* activity on the 1988 Yellowstone fires. Ecosystems 9(8):1318-1327.

Marris, E. 2011. Conservation biology: The end of the wild. Nature 469(7329):150-152.

Meyer, G.A., and J.L. Pierce. 2003. Climatic controls on fire-induced sediment pulses in Yellowstone National Park and central Idaho: A long-term perspective. Forest Ecology and Management 178:89-104.

Millspaugh, S.H., C. Whitlock, and P.J. Bartlein. 2004. Postglacial fire, vegetation, and climate history of the Yellowstone-Lamar and Central Plateau provinces, Yellowstone National Park. Pages 10-28 in L.L. Wallace, editor. After the fires: The ecology of change in Yellowstone National Park. Yale University Press, New Haven and London.

Peterson, D.L., and J.S. Littell. 2014. Risk assessment for wildfire in the western United States. Pages 232-235 in D.L. Peterson, J.M. Vose, and T. Patel-Weynand, editors. Climate change and United States forests. Springer, New York, New York, USA.

Romme, W.H., and M.G. Turner. 1991. Implications of global climate change for biogeographic patterns in the Greater Yellowstone Ecosystem. Conservation Biology 5(3):373-386.

Romme, W.H., and M.G. Turner. 1992. Global climate change in the Greater Yellowstone ecosystem. Yellowstone Science 1(1):2-5.

Romme, W.H., M.G. Turner, R.H. Gardner, W.W. Hargrove, G.A. Tuskan, D.G. Despain, and R.A. Renkin. 1997. A rare episode of sexual reproduction in aspen *(Populus tremuloides Michx.)* following the 1988 Yellowstone fires. Natural Areas Journal 17(1):17-25.

Romme, W.H., M.G. Turner, G.A Tuskan, and R.A Reed. 2005. Establishment, persistence, and growth of aspen *(Populus tremuloides)* seedlings in Yellowstone National Park. Ecology 86(2):404-418.

Romme, W.H., M.S. Boyce, R. Gresswell, E.H. Merrill, G.W. Minshall, C. Whitlock, and M.G. Turner. 2011. Twenty years after the 1988 Yellowstone fires: Lessons about disturbance and ecosystems. Ecosystems 14(7):1196-1215.

Schoennagel, T., M.G. Turner, and W.H. Romme. 2003. The influence of fire interval and serotiny on postfire lodgepole pine density in Yellowstone National Park. Ecology 84(11):2967-2978.

Shuman, B. 2012. Recent Wyoming temperature trends, their drivers, and impacts in a 14,000-year context. Climatic Change 112(2):429–447.

Simard, M., W.H. Romme, J.M. Griffin, and M.G. Turner. 2011. Do mountain pine beetle outbreaks change the probability of active crown fire in lodgepole pine forests? Ecological Monographs 81(1):3-24.

Simard, M., W.H. Romme, J.M. Griffin, and M.G. Turner. 2012. Do mountain pine beetle outbreaks change the probability of active crown fire in lodgepole pine forests? Ecology 93(4):946-950.

Smithwick, E.A.H., M.G. Ryan, D.M. Kashian, W.H. Romme, D.B. Tinker, and M.G. Turner. 2009. Modeling the effects of fire and climate change on carbon and nitrogen storage in lodgepole pine *(Pinus contorta)* stands. Global Change Biology 15(3):535-548.

Turner, M.G. 2010. Disturbance and landscape dynamics in a changing world. Ecology 91(10):2833-2849.

Turner, M.G., W.H. Romme, and D.B. Tinker. 2003a. Surprises and lessons from the 1988 Yellowstone fires. Frontiers in Ecology and the Environment 1(7):351-358.

Turner, M.G., W.H. Romme, R.A. Reed, and G.A. Tuskan. 2003b. Post-fire aspen seedling recruitment across the Yellowstone (USA) landscape. Landscape Ecology 18(2):127-140.

Turner, M.G., D.C. Donato, and W.H. Romme. 2013. Consequences of spatial heterogeneity for ecosystem services in changing forest landscapes: Priorities for future research. Landscape Ecology 28(6):1081–1097.

Westerling, A.L., H.G. Hidalgo, D.R. Cayan, and T.W. Swetnam. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science 313(5789):940-943.

Westerling A.L., M.G. Turner, E.A.H. Smithwick, W.H. Romme, and M.G. Ryan. 2011. Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. Proceedings of the National Academy of Sciences 108(32):13165-13170.

Whitlock, C., and P.J. Bartlein. 1993. Spatial variations of Holocene climatic change in the Yellowstone region. Quaternary Research 39(2):231-238.

Whitlock, C., J. Marlon, C. Briles, A. Brunelle, C. Long, and P. Bartlein. 2008. Long-term relations among fire, fuel, and climate in the north-western US based on lake-sediment studies. International Journal of Wildland Fire 17(1):72-83.

Worrall, J.J., S.B. Marchetti, L. Egeland, R.A. Mask, T. Eager, and B. Howell. 2010. Effects and etiology of sudden aspen decline in southwestern Colorado, USA. Forest Ecology and Management 260(5):638-648.

YS

William H. Romme is professor emeritus of ecology at Colorado State University. His 1979 dissertation at the University of Wyoming dealt with fire history and landscape diversity in Yellowstone National Park. Following the extensive fires in 1988, he and Monica Turner have collaborated on long-term research addressing postfire recovery of forest communities, productivity, and nutrient cycling processes. They also have investigated the impacts of fire and ungulate browsing on aspen regeneration, and the ecological effects of recent bark beetle outbreaks. Their current research in Yellowstone focuses on potential implications of climate change for fire regimes and forest regeneration.

LEADING THE WAY: *Women in Science*

A native New Yorker, **Dr. Monica G. Turner** received her BS in biology from Fordham University. Between her sophomore and junior years, an incredible summer spent in Yellowstone as a Student Conservation Association ranger-naturalist stationed at Old Faithful solidified her interest in ecology. She earned her PhD in ecology at the University of Georgia, conducting research with the National Park Service in both Cumberland Island and Virgin Islands national parks and spending one summer as a federal intern with the Man and the Biosphere Program.

She began research in Yellowstone during the summer of 1988, which began a long-term collaboration with Dr. Romme. She has continued to study disturbance regimes, vegetation dynamics, nutrient cycling, and climate change in Greater Yellowstone for over 25 years. She has published over 200 scientific papers, authored or edited six books, including *Landscape Ecology in Theory and Practice*, and is co-editor in chief of *Ecosystems*. Turner was elected to the U.S. National Academy of Sciences in 2004, and she received the Ecological Society of America's Robert H. MacArthur Award in 2008. She began serving as President-elect of the Ecological Society of America in August 2014.

As a leader in the scientific community, Dr. Turner is committed to supporting women in science. As the mother of two children, she is especially sensitive to the challenges facing young women (and men, too!) as they juggle the demands of science and family, and she advocates strongly for balance in life. It helps if you love what you do, and she frequently comments, "I feel incredibly privileged to enjoy my work so much. Life is busy and full, but I wouldn't have it any other way!"

Historic & Projected Climate Change in the Greater Yellowstone Ecosystem

Tony Chang & Dr. Andrew Hansen

Evidence of the Earth's shifting climate patterns has become more perceptible from sea and surface temperature monitoring, satellite technology, and improvements in climate modeling. At a relevant human scale, these changes are highlighted by recent hurricane events, glacial retreat, and droughts at new, unprecedented frequencies and magnitudes that have begun to reshape the landscapes. Within the Greater Yellowstone Ecosystem (GYE), regional managers and citizens have already experienced major disturbance events that have changed the system's ecology, such as increased mountain pine beetle attacks, wildfire events, and reduced annual snowpack. The fifth annual Intergovernmental Panel for Climate Change (IPCC) and the latest U.S. National Climate Assessment report a decadal global temperature increase of 1-1.2°F and a continuing upward trend.

From paleoclimate records of the GYE, changing climate has occurred before due to the natural variability of the Earth's position relative to the sun. The last major warm period occurred during the late Pleistocene and early Holocene (12,000-8,000 years ago), when the world saw the end of the last glacial maximum. The first major vegetation to move in was Engelmann spruce, followed by subalpine fir and whitebark pine, creating a widespread subalpine forest across the region. As conditions grew warmer and glaciers reached their minimum (9,500-7,500 years ago), the region became characterized by drier and warmer conditions than present day. At this period, lodgepole pine and Douglas-fir moved in from southern landscapes, pushing sub-alpine species to higher elevations (Whitlock and Bartlein 2004). Around 5,000 years ago, temperatures dropped and precipitation increased, converging towards the climate we recognize the GYE as having today.

How Has Climate Changed Within the GYE?

The Greater Yellowstone Ecosystem is a complex and fascinating region to study climate. The GYE encompasses approximately 58,000 square miles with an elevational gradient from 1,713–13,800 ft. representing 14 mountain ranges. Due to the complex mountain topography and steep elevational gradients, weather is highly variable across the region, allowing events where specific mountain ranges can encounter snowfall in one area while another experiences warm, clear skies. The region is home to some of the longest running records of temperature and precipitation anywhere in the U.S., with some weather stations initiated in 1895! Interest in snow science and variability across these mountain landscapes led to the installation of 92 active SNOwpack TELemetry (SNOTEL) stations across the GYE. SNOTEL stations are automated climate and snowpack sensors distributed across sites within the western U.S. and operated by the Natural Resource Conservation Service. These sites provide scientists with some of the highest density records of long-term weather data of anywhere in the U.S.

Although weather stations provide excellent information regarding their local site, scientists often need to know what the weather was like at higher elevation sites, in shaded valleys, or places different from where the weather stations are established. We draw on two separate data sets called the Parameter-elevation Relationships on Independent Slopes Model (PRISM) (Daly et al. 2002), and Topography Weather (TopoWx) (Oyler et al. 2014) to characterize past climate for the GYE. PRISM and TopoWx use mathematical equations based on the relationship between weather and elevation, aspect, and other factors to estimate the temperature and precipitation that occurred in locations without weather stations. The result is a weather data set of temperature and precipitation every month since 1895 (PRISM) and 1948 (TopoWx) for every 800 m square (grid) in the continental U.S. We use these data to calculate the mean annual temperatures and precipitation since the earliest available period in the GYE. Using these two gridded climate data sets, we are able to utilize their individual strengths and summarize climate for sub-areas of interest within the GYE.

Since 1948, annual temperatures across the GYE have averaged slightly above 39°F (figure 1) with an annual precipitation averaging 21.4 in/year (figure 2). Current trends indicate annual temperatures have increased by 0.31°F/decade, echoing the increasing temperature changes seen globally. Similarly, mean annual minimum and maximum temperatures have been increasing at the same rate of 0.3°F/decade for the GYE (table 1).

At a sub-regional level, we considered the temperature and precipitation averages and rates of change from 1948 to 2010, for the following areas (figure 3):

1. Yellowstone and Grand Teton national parks (YELL\GRTE)
2. Absaroka\Beartooth\N. Absaroka Wilderness Area (NA\ABT WA)
3. Washakie\Teton Wilderness Area (WA\TE WA)
4. Bridger\Fitzpatrick\Popo Agie Wilderness Area (BR\FI\PO WA)

Analysis at the sub-regional level reveal high variability across the entire GYE, with a general tendency for warming in the high elevation northern ranges of the Absaroka\Beartooth and Northern Absaroka wildernesses (0.39°F/decade) compared to the southern Wind River Range wildernesses (0.28°F/decade). Yellowstone and Grand Teton national parks as a whole followed a similar trend of warming to the entire GYE of ~0.3°F/decade (figure 4, table 1).

It should be noted that considering smaller areas of interest within the GYE possess more challenges. When we consider small regions, there is a reduction of actual stations from which the algorithms for TopoWx and PRISM can utilize to fill in the unknown areas, so there is increased uncertainty regarding sub-regional analyses, despite these data sets representing our best estimates of climate change. To overcome such uncertainty, local field observations from stream gauge and weather stations can verify some of the warming trends, and describe potential microsite conditions the ecological system may be responding to (Thoma et al., this issue).

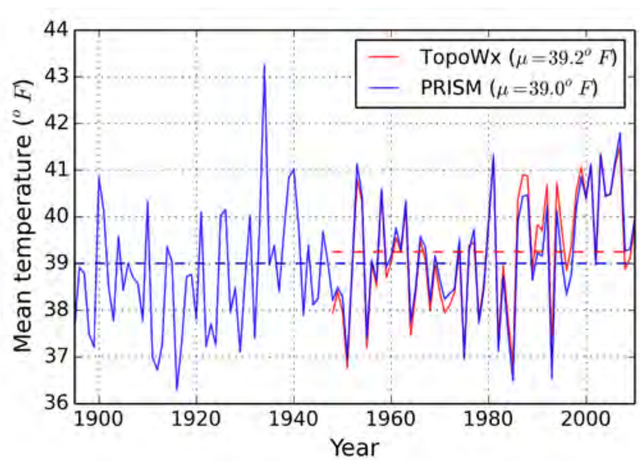


Figure 1. Mean annual temperatures averaged across the entire GYE for the past century. Dashed lines indicate the average since 1895-2010 (blue) and since 1948-2010 (red), using the PRISM and TopoWx gridded climate data sets respectively.

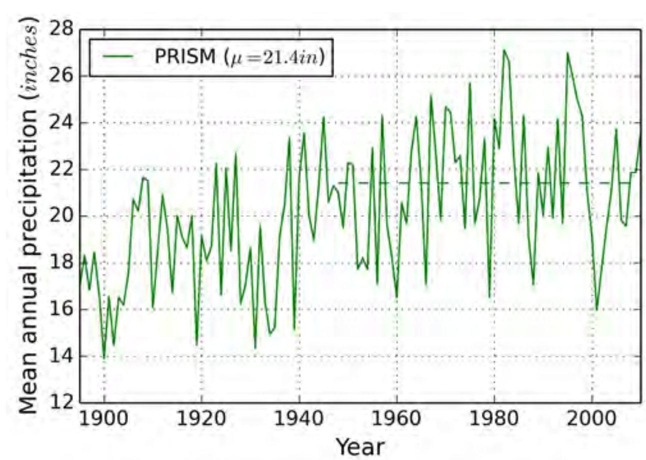


Figure 2. Mean annual precipitation averaged across the entire GYE for the past century. Dashed lines indicate the average since 1895-2010 using the PRISM gridded climate data sets. Data indicate a slight increase in precipitation over the past century at the rate of 0.4/in century.

Table 1. Summary of the regional and sub-regional mean climate conditions and median rates of change using the TopoWx data set for temperature and PRISM data set for precipitation 1948-2010.

	GYE	YELL/GRTE	NA/ABT WA	WA/TE WA	BR/FI/PO WA
T_{mean} average (°F)	37.8	34.1	33.5	33.3	32
T_{max} average (°F)	49.4	45.7	42.7	43.5	42.6
T_{min} average (°F)	26.1	22.4	23.3	23.1	21.4
P_{pt} average (in)	24.8	34.8	34.5	34.1	31.3
T_{mean} average (°F/decade)	0.31	0.29	0.39	0.31	0.28
P_{pt} average (in/decade)	0.19	0.32	0.19	0.38	0.09

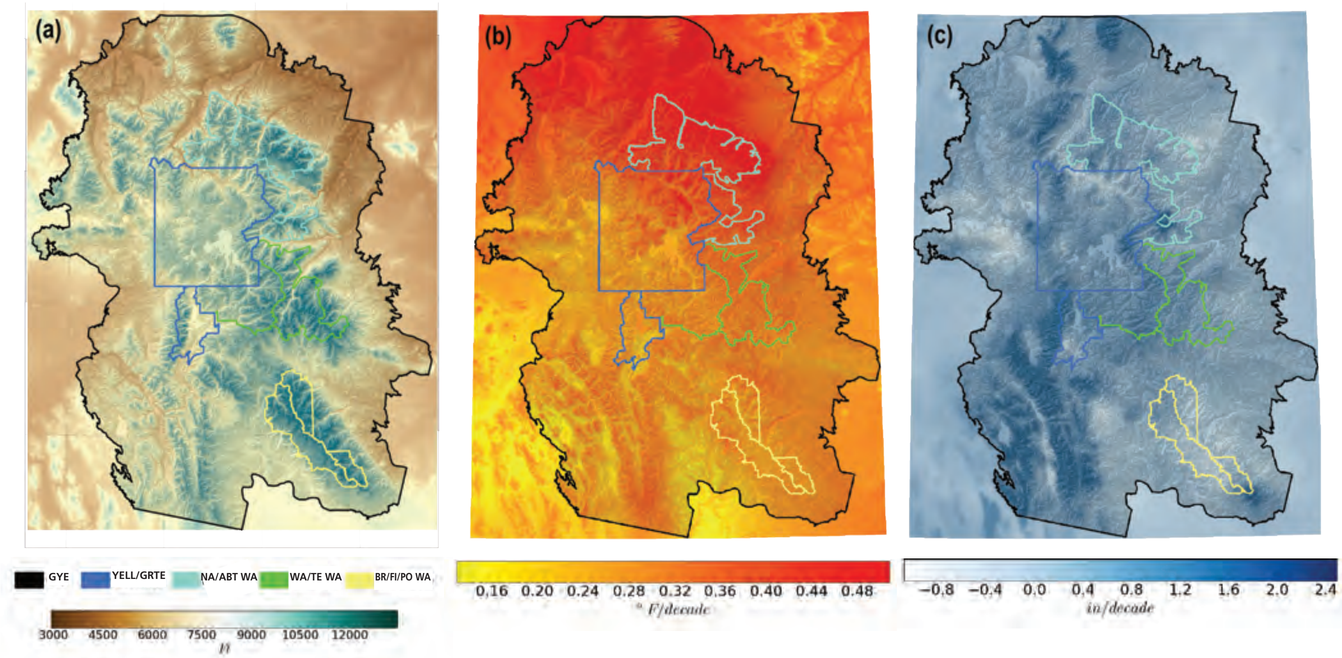


Figure 3. The Greater Yellowstone Ecosystem (58,186 square miles) and the surrounding wilderness and national park sub-regions for historic climate analysis. (a) illustrates the complex elevation gradient within the GYE region ranging from 3,000-13,800 ft. (b) TopoWx rate of change of mean annual temperatures between 1948-2010 within the GYE and sub-regions. (c) PRISM rate of change of mean annual precipitation between 1948-2010 within the GYE and sub-regions.

One example of this is the observed temperature changes influencing stream flow and temperature over the past century. Stream discharge has declined during 1950-2010 in 89% of streams analyzed in the Central Rocky Mountains, including those in the GYE (Leppi et al. 2012). Reduced flows were most pronounced during the summer months, especially in the Yellowstone River. Stream temperatures have also changed across the range of the Yellowstone, observing a warming of 1.8°F over the past century (Al-Chokhachy et al. 2013). This stream warming during the 2000s exceeded that of the Great Dust Bowl of the 1930s and represents the greatest rate of change over the past century. Continued warming could have major implications to the management and preservation of the many aquatic resources we have today.

The Projected Climate of the GYE

General Circulation Models (GCM), or global climate models, have been in development since the mid-1950s and are currently our best method of understanding and predicting the impacts of humans and natural variability on the Earth. Originally produced to computationally investigate weather patterns, rapid advances in computing allowed physics-based modeling of atmospheric patterns on the entire Earth. As computer processing speeds increased, higher modeling resolution and increased levels of complexity were able to create models with the levels of sophistication that exist today. However, despite the differences of past and present GCM complexity, they all model the same underlying general principles of motion and laws of thermodynamics that have been understood for centuries.

Today, climate models simulate not only the atmosphere but also surface and deep ocean dynamics. When ocean and atmosphere models are linked together, we refer to the GCM as 'coupled,' which result in a more realistic simulation of our planet's climate. Determination of 'realism' for GCM tend to be quantified in their ability to accurately predict the movement and evolution of disturbances, such as frontal systems and tropical cyclones. Common recognizable metrics include the ability to detect the El Nino Southern Oscillations and Pacific Decadal Oscillation. As more institutions began climate system modeling, questions regarding the impact of increased carbon emissions on temperature became prevalent. To address these questions, climate modelers generate scenarios of future potential atmospheric/ocean chemical compositions and investigate the impacts they have on the Earth's climate.

In 2013, the IPCC released the most recent projections of future climate under scenarios of greenhouse gas emissions (IPCC 2013). Some 46 global climate models were used to project climate under four Representative Concentration Pathways (RCP). RCPs are designed to characterize feasible alternative futures of the climate considering physical, demographic, economic, and social changes to the environment and atmosphere. Here we report results from two scenarios for an analysis of the GYE: RCP 4.5, which assumes stabilization in atmospheric CO_2 concentration at 560 ppm by 2100; and RCP 8.5, which assumes increases in atmospheric CO_2 concentration to 1370 ppm by 2100. Actual measured rates of greenhouse gas emissions since 2000 have been consistent with the RCP 8.5 scenario (Diffenbaugh and Field 2013, Rogelj et al. 2012). Thrasher et al. (2013) downscaled these GCM outputs to an 800-m pixel size so regional level analysis could be possible. For this GYE summary, we referenced the Rupp et al. (2013) analysis of GCMs that best represents the Pacific Northwest region.

Within the GYE, mean annual temperature is projected to rise under each of the climate scenarios. By 2100, temperature is projected to increase 6-13°F above the average for the reference period of 1900-2010 (figure 5a). Mean annual precipitation is projected to vary between 2-4 inches by 2100 (figure 5b). While temperature is projected to rise at similar rates across seasons, precipitation increases most rapidly in spring and decreases slightly in summer. Changes in aridity are projected to increase moderately under RCP 4.5 and more substantially under RCP 8.5. This suggests the current climate changing pattern we have experienced for the last 30 years will likely continue and become more severe.

Current & Projected Impacts on Ecosystems

A consequence of warming during the winter and spring months and seasonally high summer aridity has been an outbreak of forest pests causing forest die-off. Mild winter temperatures in alpine regions have been found to directly relate to the survivorship of overwintering broods of mountain pine beetle, the major disturbance agent acting on whitebark pine species (Logan and Powell 2001, Logan et al. 2010). Arid summers (high temperatures, low precipitation) likely provide a compounding effect of increasing pine beetle development

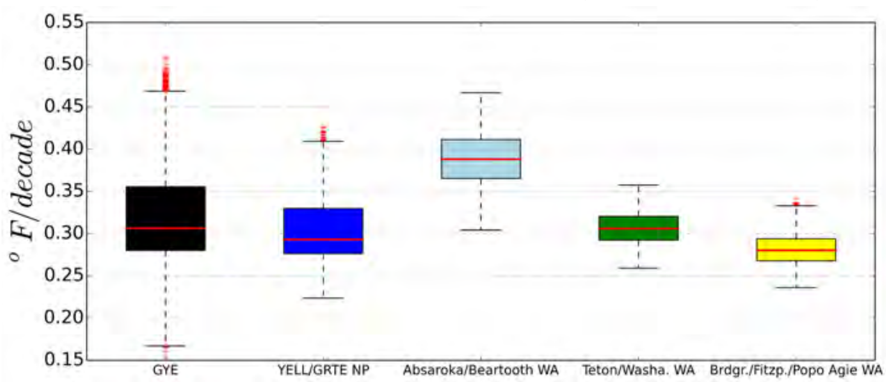


Figure 4. Box and whisker plots of warming trends across the GYE and 4 sub-regions. Northern range wilderness areas depict the greatest level of warming over 1948-2010 compared to the southern wilderness areas of the Wind River range.

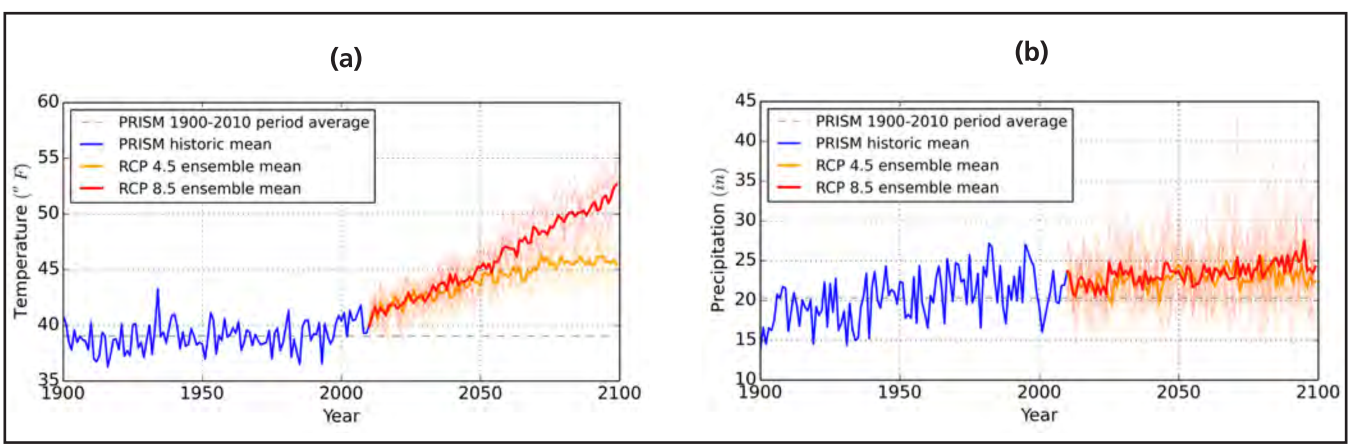


Figure 5a & 5b. GYE projections from ensemble GCMs of the Coupled Model Intercomparision Project 5 (CMIP5), the latest set of models from the IPCC Fifth Assessment Report, from 2010 to 2099 (a) mean annual temperatures, and (b) mean annual precipitation anomaly from long-term average.

rates and increasing resource stress on whitebark pine. This reduction in mortality of overwintering broods, increased development rates, and reduced tree defense can result in an expansion of the dispersal and colonization effectiveness of insect pests.

Since 1999, an eruption of mountain pine beetle events has been observed that exceed the frequencies, impacts, and ranges documented during the last 125 years (Macfarlane et al. 2013, Raffa et al. 2008). Aerial assessment of whitebark pine species populations within the GYE has indicated a 79% mortality rate of mature trees. These dramatic changes may be the first indicators of how GYE vegetation communities are to shift due to changed climate patterns.

Projected changes in climate are expected to continue to influence ecosystem processes, such as soil moisture, runoff in streams and rivers, and terrestrial net primary productivity through shifts in vegetative communities. The projected warming results in April 1 snowpack declining 3.2-4.3 inches by 2100. The reduction in snowpack is most pronounced in spring and summer, with the GYE projected to be largely snow free on April 1 by 2075 under RCP 8.5. Average annual soil water projections show considerable inter-annual variability, but have a shallow positive trend, increasing about 0.4 inches by 2100 with increases mostly in spring and a slight decline in summer. Mean annual runoff increases more rapidly, with pronounced increases in spring and decreases in summer. The projected pattern for gross primary productivity also increases annually in spring and decreases in summer.

Stream temperatures are projected to increase between 1.4-3.2°F by 2050 to 2069 (Al-Chokhachy et al. 2013). Yellowstone cutthroat trout are projected to decline by 26% in response to this temperature increase due to its positive influence on nonnative species (Wenger et al. 2011). In uplands, warming temperatures are projected to result in severe wildfires becoming more common within the GYE (Westerling et al. 2011), which could result in major changes in vegetation type and seral stage.

One way to gauge potential effects of projected climate change on vegetation is to determine the climate conditions within which a vegetation type currently occurs and map locations projected to be within this range of climate conditions in the future. While dispersal limitations, competition from other species, disturbances, etc., may prevent vegetation from establishing in areas with newly suitable climates, this method is a meaningful way to interpret climate from a vegetation perspective. Piekielek et al. (in preparation) projected suitable climatic conditions to decrease for the subalpine conifer forest and alpine tundra biome types and increase largely for Great Basin montane scrub biome type and slightly increase for montane conifers such as Douglas-fir (see Hansen et al., this issue). If vegetation changes in parallel with these climates, these results suggest snowpack, runoff, and net primary productivity would be substantially reduced.

A New Status Quo

These results indicate climate has and will continue to change substantially. Our summary of projected climate suggests the future will experience temperatures higher than any time in the warm periods of the Holocene. This rapid temperature change can result in substantial reductions in snowpack and stream runoff and increases in stream temperature, fire frequency, and mortality of currently dominant tree species. One possible future is for the system to move into a new state with little summer snow, very low stream flows, frequent and severe fire, and switch from forest-dominated vegetation to desert scrub vegetation. Such changes will challenge resource managers in the effort to ensure the health and integrity of this complex natural system while still providing the recreational experiences the public has come to expect. Strategies for adaptation and mitigation in natural resource management should be considered given the magnitude of potential future ecosystem impacts.

Literature Cited

Al-Chokhachy, R., J. Alder, S. Hostetler, R. Gresswell, and B. Shepard. 2013. Thermal controls of Yellowstone cutthroat trout and invasive fishes under climate change. Global Change Biology 19(10):3069-3081.

Daly, C., W.P. Gibson, G.H. Taylor, G.L. Johnson, and P. Pasteris. 2002. A knowledge-based approach to the statistical mapping of climate. Climate Research. 22:99-113.

Diffenbaugh, N.S., and C.B. Field. 2013. Changes in ecologically critical terrestrial climate conditions. Science 341(6145):486-492.

Hansen, A.J., C.R. Davis, N. Piekielek, J. Gross, D.M. Theobald, S. Goetz, F. Melton, and R. DeFries. 2011. Delineating the ecosystems containing protected areas for monitoring and management. BioScience 61(5):363-373.

IPCC WGI AR5. 2013. Summary for policymakers. Pages 3-32 in Stocker, T.F., D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, editors. Climate change 2013: The physical science basis. Cambridge Univ Press, New York.

Leppi, J.C., T.H. DeLuca, S.W. Harrar, and S.W. Running. 2012. Impacts of climate change on August stream discharge in the Central-Rocky Mountains. Climatic Change 112:997-1014.

Logan, J.A.,, W.W. Macfarlane, and L. Willcox. 2010. Whitebark pine vulnerability to climate-driven mountain pine beetle disturbance in the Greater Yellowstone Ecosystem. Ecological Applications 20(4):895-902.

Logan, J.A., and J.A. Powell. 2001. Ghost forests, global warming, and the mountain pine beetle (Coleoptera: Scolytidae). American Entomologist 47(3):160-173.

Macfarlane, W.W., J.A. Logan, and W.R. Kern. 2013. An innovative aerial assessment of Greater Yellowstone Ecosystem mountain pine beetle-caused whitebark pine mortality. Ecological Applications 23(2):421–437.

Oyler, J.W., A. Ballantyne, K. Jensco, M. Sweet, and S.W. Running. 2014. Creating a topoclimatic daily air temperature dataset for the conterminous United States using homogenized station data and remotely sensed land skin temperature. Journal of Climatology. DOI: 10.1002/joc.4127.

Piekielek, N.B., A.J. Hansen, and T. Chang. In preparation. Projected future changes in spring snow pack and late summer soil water deficit suggest decline in habitat suitability for most forest species in the Greater Yellowstone Ecosystem, U.S.

Raffa, K.F., B.H. Aukema, B.J. Bentz, A.L. Carroll, J.A. Hicke, M.G. Turner, and W.H. Romme. 2008. Cross-scale drivers of natural disturbances prone to anthropogenic amplifcation: the dynamics of bark beetle eruptions. Bioscience 58(6):501-517.

Rogelj, J., M. Meinshausen, and R. Knutti. 2012. Global warming under old and new scenarios using IPCC climate sensitivity range estimates. Nature Climate Change 2(4):248-253.

Rupp, D.E., J.T. Abatzoglou, K.C. Hegewisch, and P.W. Mote. 2013. Evaluation of SMIP5 20th century climate simulations for the Pacific Northwest USA. Journal of Geophysical Research: Atmospheres 118:110-884.

Thrasher, B., J. Xiong, W. Wang, F. Melton, and A. Michaelis. 2013. Downscaled climate projections suitable for resource management. EOS 94(37):321-323.

Wenger, S.J., D.J. Isaak, C.H. Luce, H.M. Neville, K.D. Fausch, J.B. Dunham, D.C. Dauwalter, M.K. Young, M.M. Elsner, B.E. Rieman, A.F. Hamlet, and J.E. Williams. 2011. Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. Proceedings of the National Academy of Sciences 108(34):14175-14180.

Westerling, A.L., M.G. Turner, E.A. Smithwick, W.H. Romme, and M.G. Ryan. 2011. Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. Proceedings of the National Academy of Sciences 108(32):13165-13170.

Whitlock, C., and P.J. Bartlein. 2004. Holocene fire activity as a record of past environmental change. Pages 479-489 in Gillespie, A.R., S.C. Porter, and B.F. Atwater, editors. Developments in Quaternary Science Volume 1. Elsevier, Amsterdam.

YS

Tony Chang is a 3rd year PhD student in Ecology at Montana State University and was recently awarded the NASA Earth and Space Science Fellowship. His research focuses on statistical and process based ecosystem models for whitebark pine and mountain pine beetle within the Greater Yellowstone Area under climate change. Tony received his BS from UCLA in Mechanical Engineering specializing in Design and Modeling, and his MS from Northern Arizona University in Environmental Science and Policy.

Andrew Hansen is a professor in the Ecology Department at Montana State University. He studies how land use and climate change influence plants and animals, and implications for ecosystem management, especially in the context of protected areas.

Trends in Yellowstone's Snowpack

Dr. Mike Tercek, Ann Rodman, & Dr. David Thoma

If water is the source of life, then life in Yellowstone is ruled by snow. In the park's highest elevations, snow often covers the ground until late June. Even in a desert like Gardiner, Montana (MT), melting snow controls the pattern of water availability for the entire year, as seen by the stream flow on the Yellowstone River at Corwin Springs, MT, next to Yellowstone's northern boundary (figure 1).

Each year, flow is characterized by a large spike that begins when snow starts to melt at lower elevations, usually at the end of February or the beginning of March. Peak flow is reached sometime in June when the deep snow fields at medium and high elevations are melting quickly. Minimum flow occurs when all the year's snow has melted and it is cold enough for precipitation to fall as snow instead of rain, so only water flowing from underground sources can supply the streams. Year after year, the hydrograph is dominated by this pattern of snow melt (figure 1). The proportion of stream flow to the annual snow cycle due to rain storms is merely a blip in comparison.

The influence of Yellowstone's snow reaches beyond the park's boundaries. The Yellowstone River, the Snake River, and the Green River have headwaters in the mountains in and near Yellowstone National Park. These rivers, in turn, are the largest tributaries of the Missouri, Columbia, and Colorado rivers, respectively (figure 2). Millions of people living on all sides of Yellowstone rely on these rivers for agriculture, drinking water, recreation, and energy production. If Yellowstone receives less snow in the future, the consequences would be widespread.

How does the snowpack in recent years compare to the past and are there long-term trends in Yellowstone's snow data? How much change is attributed to natural climate cycles vs. anthropogenic (human-caused) climate change? This article addresses these questions using data from Yellowstone's manual snow courses and automated Snow-Telemetry (SNOTEL) weather stations.

Analysis of Snow Water Content

Our analyses focused on snow water equivalent (SWE), or the amount of water in the snow, usually expressed as inches. If you melted all the snow from one place and measured the depth of that water, it equates to the snow water equivalent. Ten inches of snow depth might contain only 2 or 3 inches of water and 7 or 8 inches of fluffy air between the flakes. Since the density (fluffiness) of snow changes as it settles, partially melts, and refreezes, snow depth can change a lot in just a day or two,

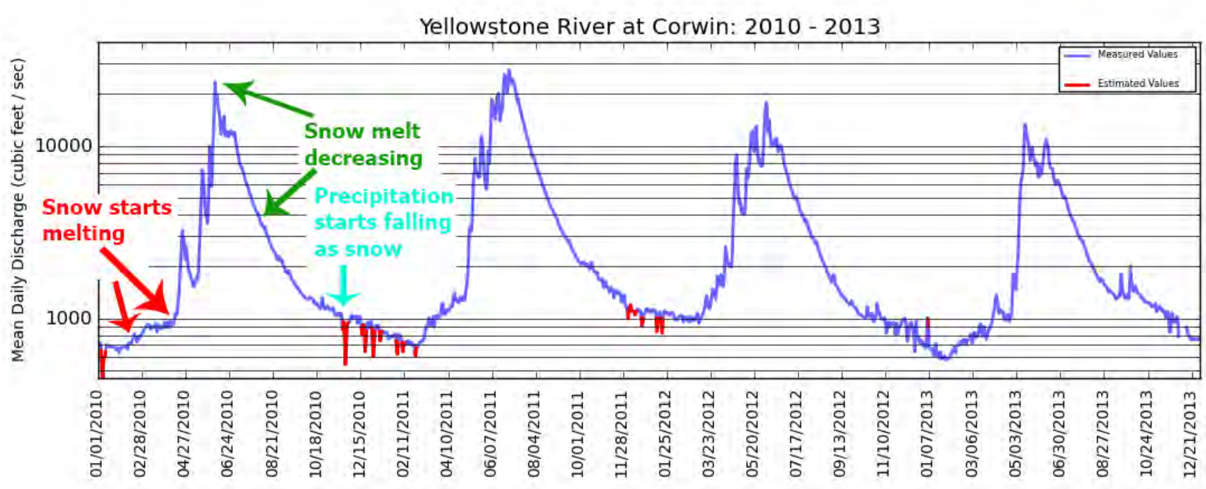


Figure 1. Mean daily stream flow on the Yellowstone River at Corwin Springs, Montana, 2010–2013. The y-axis is logarithmic, meaning each major division is 10 times greater than the previous (e.g., 1,000 vs. 10,000). Data source: U.S. Geological Survey.

Figure 2. Map showing Yellowstone National Park watershed (grey) and its connection to the Columbia, Missouri, and Green river watersheds.[1]

[1] Marcus, W.A., J.E. Meacham, A.W. Rodman, and A.Y. Steingisser. 2012. Atlas of Yellowstone. University of California Press, University of Califonia Press, Berkeley, CA, USA.

but the amount of water on the ground (SWE) will remain relatively constant. When comparing the amount of snow at different locations, it is easier to think in terms of SWE rather than depth because there are no complications resulting from snow being fluffy in one place and dense and compacted somewhere else. If someone wants to predict spring flooding, it is important to know how much snow water is going to melt. Snow depth is less important.

We used two types of SWE data: snow courses and SNOTEL weather stations. Snow courses are manual measurements of water content in a snowpack taken by people who hike or ski to pre-chosen locations once or twice a month, as close as possible to the same time every year. Measurements from snow courses extend back as far as 1919 in the Yellowstone area, but in many cases were discontinued and replaced by automated SNOTEL stations. SNOTEL stations have the advantage of providing detailed daily measurements, but their records typically begin in the 1980s (in some cases as early as the 1960s). They are not directly comparable to snow courses because of differences in the methods used to measure snow. Both SNOTEL and snow courses are operated by the Natural Resources Conservation Service (more information on their methods can be found at http://www.wcc.nrcs.usda.gov/snow/).

In figure 3, the y-axis is the SWE on April 1 during each year. April 1 was chosen because snow course data were collected on the 1st and/or 15th of every month, and April 1 is, in many locations, the date closest to the peak (greatest) SWE of the year. In the years when SNOTEL and snow course measurements overlapped (1988 – 2012), there are small differences in SWE recorded by the different methods. These differences make it impossible to directly compare the two types of data, so statistical methods (ordinary least squares linear regressions) were used to connect the two data sets into a single time series that could be tested to determine if there was a significant change over time. In some locations, the snow course measurements continue to the present-day so no correction was needed. In order to test for trends in April 1 SWE, we used non-parametric, regression-based statistical techniques appropriate for hydrological data (Bayazit and Onoz 2007, Sen 1968).

Long-Term Trends from the Oldest Sites

Results are dependent on the length of the record being examined. Of the 30 snow course / SNOTEL locations examined, only ten had data beginning before 1938 (figure 4, left panel), and four (Glade Creek, Huckleberry Divide, Lewis Lake Divide, Snake River stations) had data extending back to 1919. These older locations are important because they include snow records from the great "Dust Bowl" drought of the 1930s. It turns out April 1 SWE levels during the Dust Bowl were very similar to April 1 SWE levels during the 2000s. As a result, statistical tests on these longer data sets detected no significant increase or decrease over the record period.

If, instead of beginning our analysis at Snake River Station in 1919, we had chosen a starting year of 1978, then we would have detected a significant decline in snow at this location simply because our starting point was during a very snowy decade (figure 3). This pattern holds across most of the locations examined: snowpack was generally low during the 2000s and the 1930s (when data for that time period are available) and high during the 1970s through the mid-1980s.

More Recent Trends from All Locations

How do the trends in April 1 SWE differ from site to site? The longer records just described (pre-1938), are only one-third of the available data. In order to determine spatial (place-to-place) differences in the patterns of snowpack change, we needed to pick a common time period for all available locations (figure 4, right panel). Every location starts in a different year, so it would not be valid to analyze all available years from each location. Such a procedure would mix the effects of different time periods with the spatial variation we are investigating.

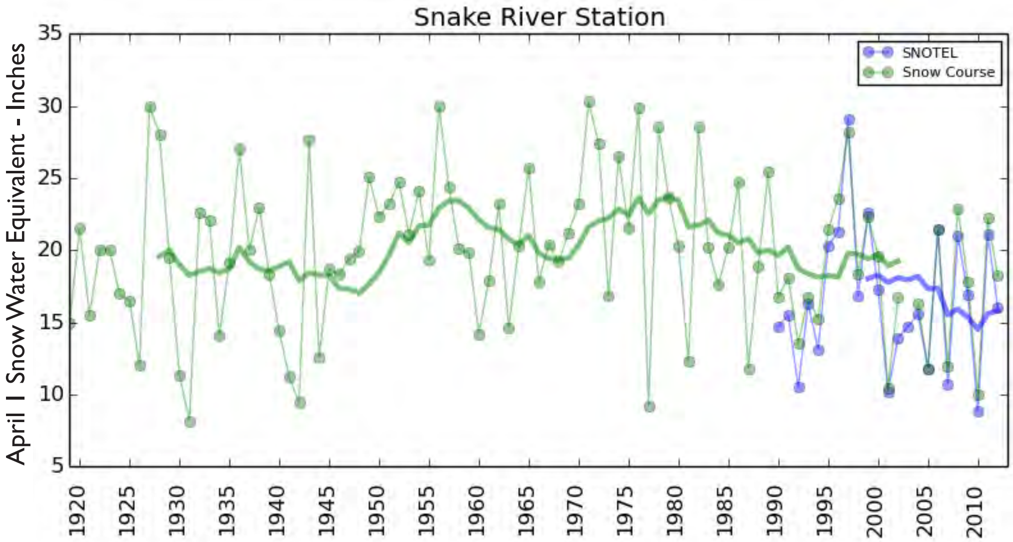


Figure 3. Snow course and SNOTEL data collected at Snake River Station (south gate), Yellowstone National Park. Green circles represent snow course measurements from 1920 to 2012 and blue circles are automated SNOTEL measurements from 1988 to 2012. Ten-year running averages (heavy lines) are calculated as the average of the current year and the previous nine years.

Consequently, we re-ran our trend analysis using the same methods described above for the years 1961–2012 because it was the longest time period common to all of our snow course / SNOTEL sites. We found 70% (21/30) of the sites had significant declines during this 52-year period (figure 4, right panel).

Why did some locations experience snow losses while others stayed more or less constant? In general, no temperature and precipitation measurements were taken at the same locations as our snow courses. Some sites did not have thermometers installed until late in the record and many snow courses never had weather stations established. In order to investigate this question, we reconstructed historical patterns at each snow course using estimated values from the Parameter-elevation Relationships on Independent Slopes Model (PRISM, Daly et al. 2008), which is a map data set that estimates the climate for every location in the continental United States by interpolating (filling-in) the spaces between weather stations. There is probably no "one-size-fits-all" explanation for every site in figure 4 (right panel). We did find, taken as an average, sites with declining snowpack during 1961–2012 generally had lower precipitation (not shown) and higher average daily maximum temperatures during the winter months. These patterns suggest increasing temperatures during January, February, March, and April have caused significant snow declines in locations with higher average temperatures by pushing them over the freezing point more often. Other factors contributing to site-to-site differences in snowpack patterns include wind scouring (removes snow) and amount of tree cover (protects snow from sun and wind). Interestingly, the elevations of declining vs. no-trend sites overlapped and were not a good explanation of site-to-site differences.

At first glance, differences in figure 5 might seem unimportant. During the month of March, locations with declining snowpack had daily maximum temperatures only 2–3°F warmer, on average. How much difference could a few degrees make? Remember that the temperatures shown in figure 5 are the monthly averages of the warmest daily temperatures, and the monthly averages for each site have been averaged into two lines (declining vs. no-trend lines). A small difference in averages matters because averages are merely middle values in an entire distribution (bell curve) of temperatures. Usually, two temperature distributions with seemingly similar averages will have much larger differences in the hottest temperatures measured (for further explanation, see "A seemingly small change in average temperature can have big effects" by Mike Tercek in this issue of *Yellowstone Science*). As a result of these differences between temperature distributions, there are many more days above freezing, and further above freezing, at the declining locations than at the no-trend locations.

Temperature increases are likely the primary cause of the snow declines documented during 1961–2012. Locations with snow declines were already warmer (and in some cases had less precipitation), making them more susceptible to warming occurring parkwide. Locations that were generally wetter and cooler (yellow circles, figure 4) have not yet demonstrated declines, but with continued climate change (Collins et al. 2013) will begin to lose their snowpack too. Even though the increases in average temperatures during 1961–2012 were not large, the shift in averages resulted in an increased number of days above freezing, which melts snow. We cannot directly count the number of days above freezing at our snow course locations because the mapped PRISM data used to reconstruct temperature are available only as monthly averages, but we do feel confident in saying there has been an increase in the number of days above freezing because this pattern occurs at many weather stations across the park where there has been a similar shift in average temperatures. Figure 6 illustrates there have been 80–100 more days above freezing during recent years than during the mid-1980s at the Northeast Entrance to Yellowstone. In other words, the season during which temperatures are above freezing is roughly 3 months longer now than it was 25 years ago at the Northeast Entrance.

A Broader Perspective

We have seen that the longest snow course records in Yellowstone had no significant gain or loss of April 1 SWE from the early 20th century to present day because they include both low snow eras of the Dust Bowl 1930s and the 2000s. Graphs of April 1 SWE from these locations have two low points at the beginning and the end, with a bubble of higher snow years during the 1970s–1980s (figure 3). If we shorten the length of our analysis to 1961–2012, so there is a common time period shared by all snow courses in Yellowstone (figure 4, right panel), we find significant declines at some locations but not at others. The first analysis (figure 4, left panel) gives a long-term perspective, and the second analysis (figure 4, right panel) helps us to determine if some locations are changing differently than others.

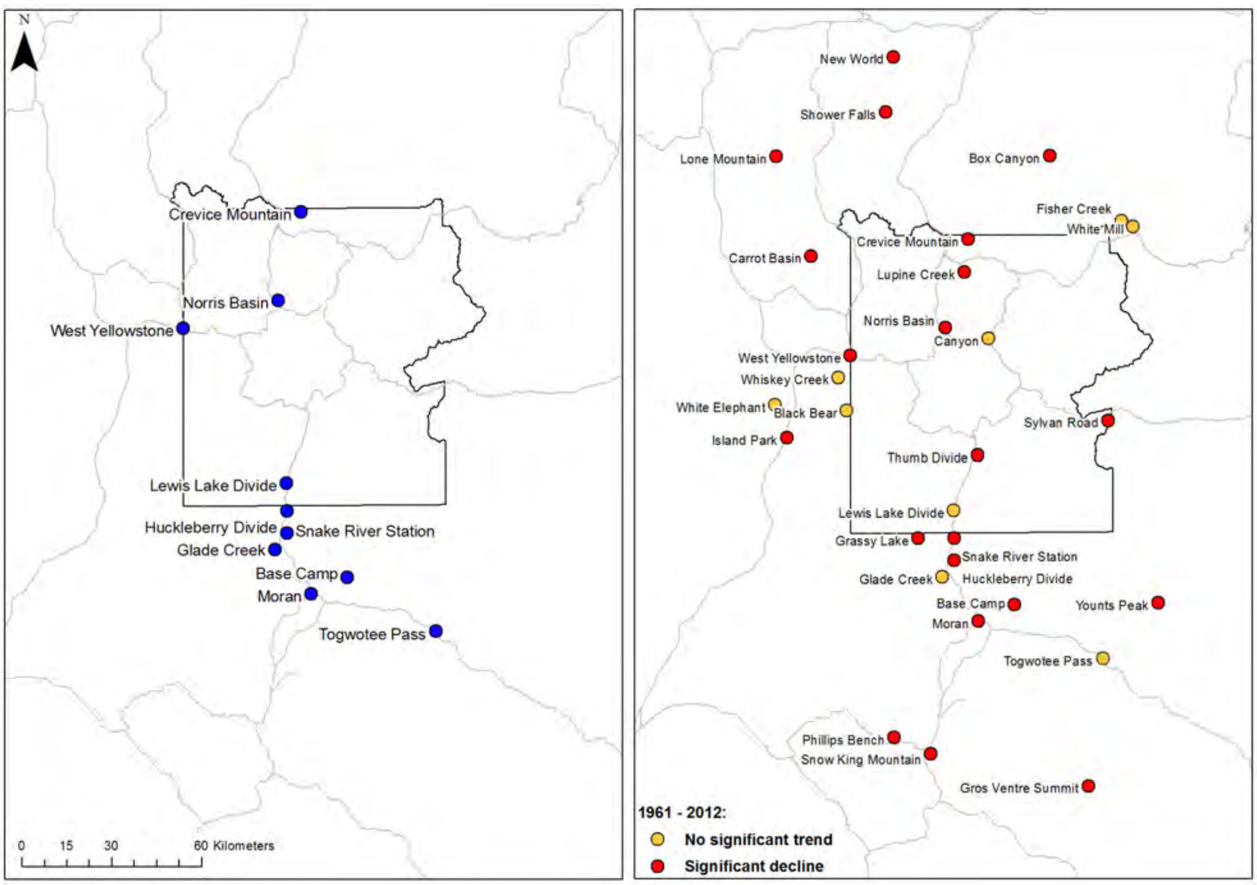


Figure 4. Left: Snow course / SNOTEL locations with data beginning before 1938. These locations had no statistically significant increases or decreases in April 1 SWE for their record period. Right: Snow course / SNOTEL locations with data during the common reference period of 1961 to 2012. Red circles indicate locations with statistically significant declines ($p < 0.1$) in April 1 SWE during this period. Yellow circles indicate locations with no significant increase or decrease during this period. Dark outline is Yellowstone National Park boundary and light lines are major roads.

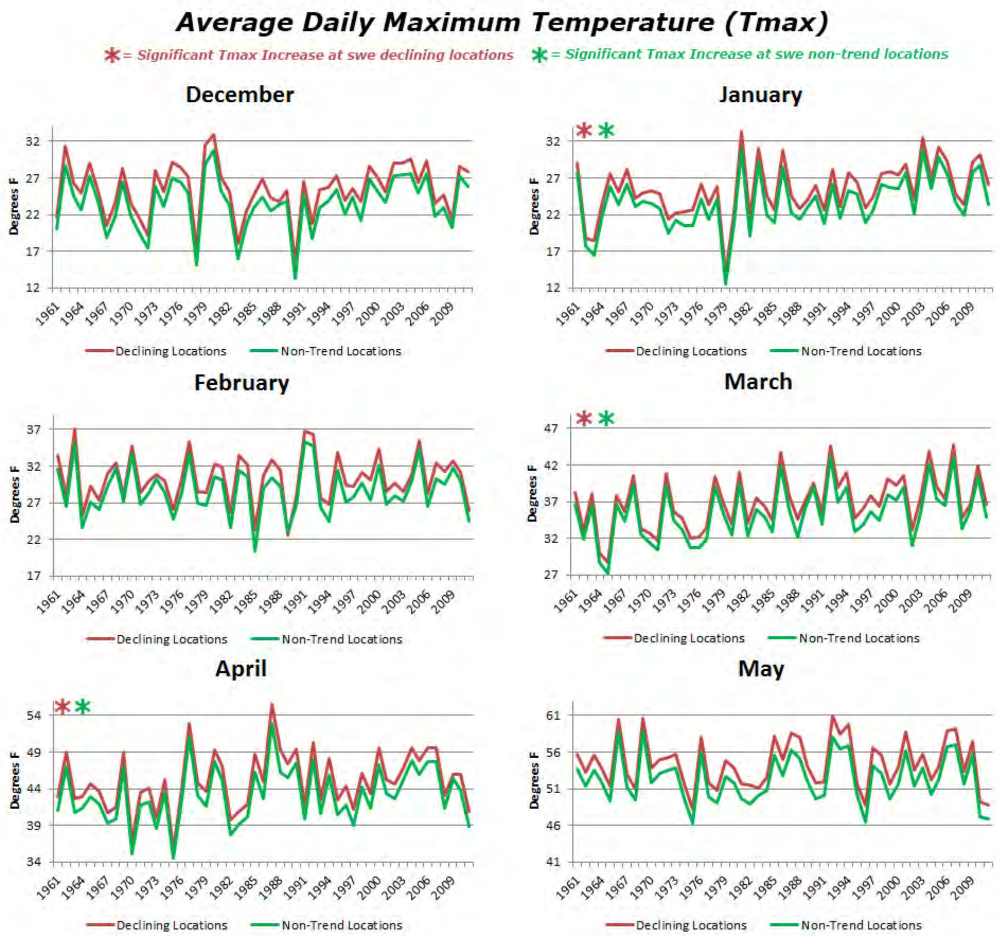


Figure 5. Monthly average daily maximum temperature (Tmax) during 1961 to 2012 at snow course and SNOTEL locations in and near Yellowstone National Park. Red lines are average temperatures for all sites with declining April 1 SWE during 1961 to 2012. Green lines are average temperatures for all sites with no significant increase or decrease during 1961 to 2012. Asterisks indicate months with a Tmax significant increase ($p < 0.05$) during 1961 to 2012.

These results raise two questions. First, if the longer records showed no significant increases or decreases in April 1 SWE, why is there so much coverage in the media about global warming and climate change? Second, are the changes in snowpack seen in Yellowstone due to natural climate cycles or human-caused climate change?

To answer the first question, we turn to longer estimates of April 1 SWE reconstructed from tree ring records (Pederson et al. 2011b). Annual tree ring width is a highly accurate proxy for precipitation. Figure 7 is a zoomed-out version of the pattern seen in figure 3. Instead of using just April 1 SWE from 1919 to 2012, it shows a combined average of all the sites in the Greater Yellowstone Ecosystem from 1200 AD to the present. Red arrows in figure 7 indicate the same low points during the 1930s and 2000s as seen in figure 3. With this added perspective, we can see these two drought periods were not just the driest in living memory but were actually the lowest snow years in the past 800 years. As stated earlier, the results of our trend analysis depended on which years you choose to include, and now we see that is doubly true. Our analysis of the longer, pre-1938 snow courses (figure 4, left panel) by chance showed no trend because it included the two periods of lowest snowpack ever recorded at its start and end points. If we had used tree ring records and calculated a trend line over the last 800 years, we would have concluded Yellowstone was experiencing severe snow decline.

This brings us to answering our second question: how much of the change seen in Yellowstone's snowpack can be attributed to natural vs. human causes? Intuitively, snowpack declines could be attributed to either increased temperatures or reduced precipitation, or a combination of the two. It also seems possible changes in temperature and precipitation might be due to a combination of both

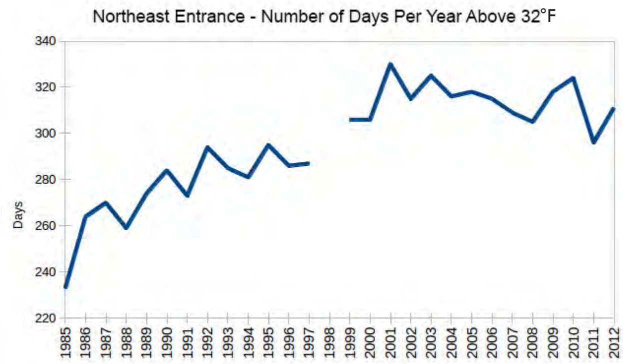


Figure 6. Number of days per year above 32°F at Yellowstone's Northeast Entrance from 1985 to 2012. Temperature measurements at this weather station did not begin until 1985. Similar patterns are seen throughout Yellowstone.

natural and human causes. It would be reasonable to rephrase our question to ask: how do we know snowpack will not recover? Will natural cycles bring snowpack back up to the long-term, 800-year average?

Natural cycles called "teleconnections" do significantly affect many aspects of climate in the western U.S., including snowpack, precipitation, and drought (Graumlich et al. 2003, Mote 2006, Pederson et al. 2011a, Schoennagel et al. 2005). The most familiar teleconnection is the El-Nino Southern Oscillation (ENSO), which affects precipitation in Yellowstone on a roughly 3–7 year cycle. In years when sea surface temperatures are warmer in the South Pacific (an "El Nino year"), ENSO pushes wet air moving from the Pacific Ocean east toward Yellowstone more slightly south, producing less precipitation in the southern part of the park and (sometimes) more precipitation in the north. There are a dozen other cycles operating over different time scales and connecting different parts of the atmosphere or ocean to each other. Yellowstone is actually located right on the boundary of two zones that respond in opposite ways to ENSO and its longer-lived cousin, the Pacific Decadal Oscillation (PDO), which changes the direction of its influence every 10–30 years (Mote 2006, Pederson et al. 2011b).

As a result of Yellowstone's unique position straddling these climatic boundaries, the influence of ENSO and the PDO teleconnections can be quite different at different locations. Our calculations find 2-50% of the variability in April 1 SWE can be explained by fluctuations in the PDO, depending on the location being examined. This very wide range of influence shows no discernible geographic pattern to which sites are more affected. Two sites very close to each other often have very different degrees of response to the PDO, and there is no correlation between sites that respond to PDO and sites showing snowpack declines during 1961–2012 (figure 4).

So, natural cycles are important, but they are not the primary influence of snowpack levels. Results from other research (Kapnick and Hall 2012, Mote 2006, Pedersen et al. 2011b) support our conclusion that long-term snowpack declines are caused by temperature increases and the pattern is found across the western U.S. More importantly, these temperature increases are moving in one direction instead of cycling. If natural cycles were the only factor influencing snow, then a graph of long-term trends would gently wave up and down but not significantly increase or decrease. Instead, long-term reconstructions of past and future predictions for snowpack (figure 7; Collins et al. 2013, Pederson et al. 2011b) show a declining stair-step pattern. Human-caused climate change is providing the downward slope for the stairs and

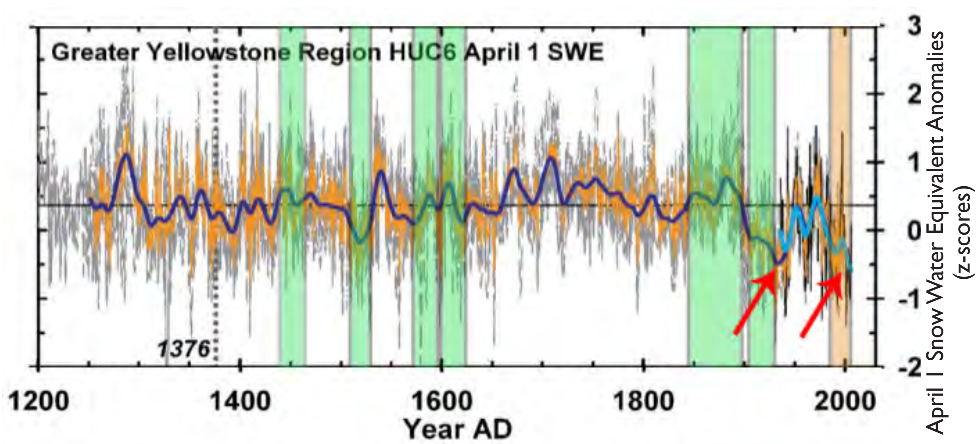


Figure 7. April 1 SWE reconstructed from tree rings, taken from Pederson et al. 2011b. Red arrows (added by authors) point out the 1930s and the 2000s which had the lowest snowpack in 800 years. The y-axis is expressed as z-scores, which are the number of standard deviations that a measurement departs from the long-term average.

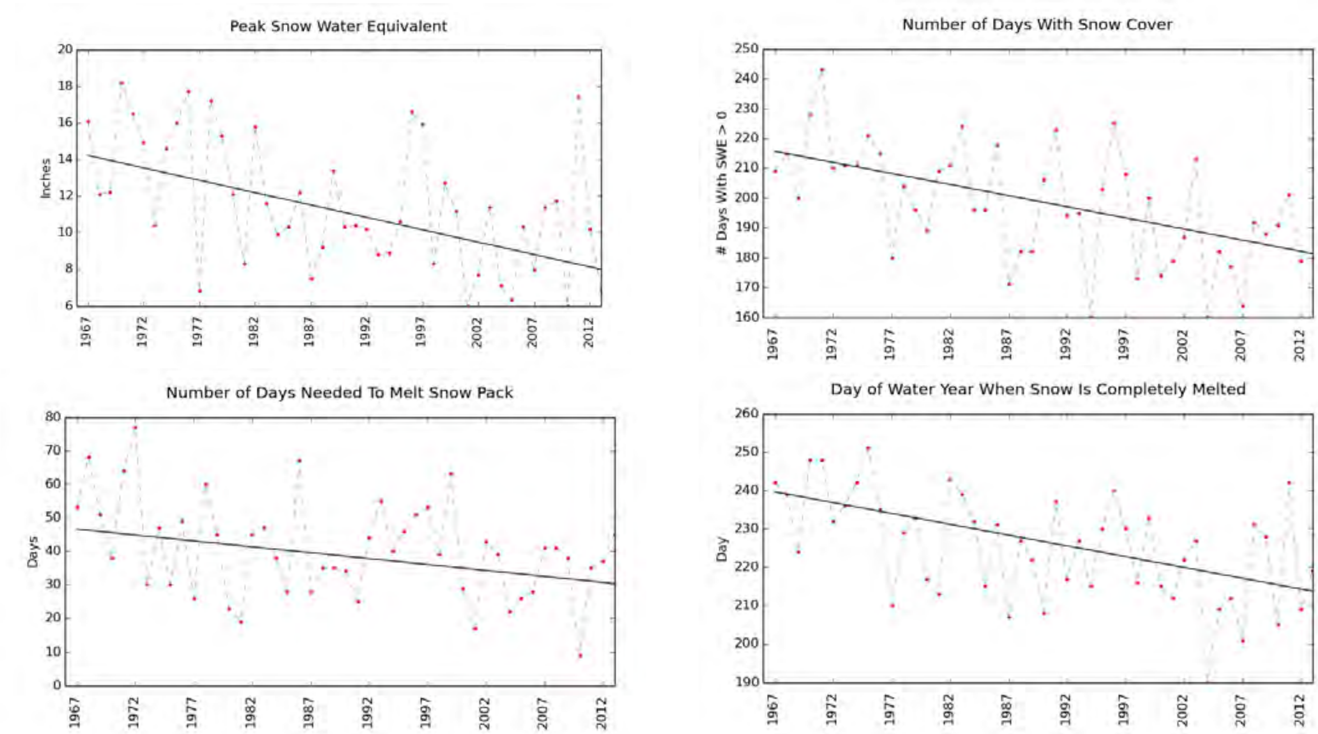


Figure 8. Winter trends at Yellowstone's Northeast Entrance, 1966 to 2013. The x-axes show water-years, which run from October 1 to September 30 of the next year. The y-axis on the bottom-right graph shows the number of days after the start of each water year (e.g., day 240 in the bottom right graph would be May 29 in a non-leap-year).

natural cycles, like the PDO and ENSO, are providing the flat places and gentle increases making up the steps. It is possible the next few decades will have more snow than the dry years of the 2000s; but when the teleconnections affecting snow in our region switch back to the dry cycle, the resulting drought will likely be one step lower on the staircase.

Finally, we note April 1 SWE is only one measurement and many other types of data from Yellowstone's weather stations confirm temperature increases are driving snowpack declines. Figure 8 shows the peak (greatest) snow water equivalent (regardless of date of occurrence), the length of snow season (days), and the number of days needed to melt the snowpack have all declined significantly ($p < 0.05$) at the Northeast Entrance since records began in 1966. In other words, there is less total snow, for fewer days each year, and it is melting faster. The "winter" at this location is roughly one month shorter than it was 45 years ago because of a progressively earlier spring (figure 8, bottom right). Analyses of all SNOTEL stations in and near Yellowstone with more than 30 years of available data are showing similar patterns at many locations.

The Long-Term Forecast is for Less Snow in Yellowstone

Looking for climate data trends is not as simple as it might seem. As observed in our research, the years chosen for the starting and ending points of analysis have a big effect on the final result, and finding a pattern takes more work than just graphing the data and "eyeballing" the slope of the line. Since climate data has a lot of noisy variability and fluctuations that can hide trends, it is important to use correct statistical procedures and apply them to periods of time that are long enough to reveal patterns within the noise (usually at least 30 years). Additionally, changes in measurement methods (e.g., manual snow course vs. automated SNOTEL), changes in equipment, changes in weather station locations, and many other factors make trend analysis a tedious and difficult process. Despite all these caveats and complications, we are confident in saying the long-term forecast in Yellowstone calls for less snow. There may be a few decades-long bumps and flat places in the trend, but the overall picture of a declining staircase is clear. People who rely on water that begins its life as snow in the mountains of Yellowstone should be aware of this fact and plan accordingly.

Acknowledgements

We would like to thank park rangers and staff for their dedication hiking and skiing to the snow course sites in difficult conditions every year, for 95 years. Without them, the high quality data sets presented in this article would not exist. We also thank the NRCS for operating and maintaining the snow course and SNOTEL sites within Yellowstone.

Literature Cited

Bayazit, M., and B. Onoz. 2007. To prewhiten or not to prewhiten in trend analysis. Hydrological Sciences Journal 52(4):611-624.

Collins, M., R. Knutti, J. Arblaster, J.L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver, and M. Wehner. 2013. Long-term climate change: Projections, commitments and irreversibility. Pages 1029-1136 in T.F. Stocker, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, editors. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Daly C., M. Halbleib, J. Smith, W. Gibson, M. Doggett, G. Taylor, J. Curtis, and P. Pasteris. 2008. Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. International Journal of Climatology 28(15):2031–2064.

Graumlich, L., M. Pisaric, L. Waggoner, J. Littell, and J. King. 2003. Upper Yellowstone River flow and teleconnections with pacific basin climate variability during the past three centuries. Climatic Change 59:245–262.

Kapnick, S., and A. Hall. 2012. Causes of recent changes in western North American snowpack. Climate Dynamics 38:1885–1899.

Mote, P. 2006. Climate-driven variability and trends in mountain snowpack in western North America. Journal of Climate 19(23):6209–6220.

Pederson, G., S. Gray, T. Ault, W. Marsh, D. Fagre, A. Bunn, C. Woodhouse, and L. Graumlich. 2011a. Climatic controls on the snowmelt hydrology of the northern Rocky Mountains. Journal of Climate 24(6):1666–1687.

Pederson, G., S. Gray, C. Woodhouse, J. Betancourt, D. Fagre, J. Littell, E. Watson, B. Luckman, and L. Graumlich. 2011b. The unusual nature of recent snowpack declines in the North American cordillera. Science 333:332-335.

Schoennagel, T., T. Veblen, W. Romme, J. Sibold, and E. Cook. 2005. ENSO and PDO variability affect drought-induced fire occurrence in Rocky Mountain subapline forests. Ecological Applications 15(6):2000–2014.

Sen, P. 1968. Estimates of the regression coefficient based on Kendall's Tau. Journal of the American Statistical Association 63:1379-1389.

YS

Mike Tercek, PhD, has worked in Yellowstone for 25 years. Osborne Russell expressed it best when he visited Lamar Valley in the 1830s:

> *"I wished I could spend the remainder of my days in a place like this where happiness and contentment seemed to reign in wild romantic splendor..."*

He is sole proprietor of Walking Shadow Ecology (www.YellowstoneEcology.com) in Gardiner, MT. Mike is pictured on the following page with his young daughter in Grand Teton National Park.

David Thoma is a scientist with the National Park Service Inventory and Monitoring Program in Bozeman, MT. He uses a water balance model and satellite remote sensing to understand broad-scale relationships between climate and biology.

Ann Rodman, see page 5.


Photo by Ashea Mills ©

Water in the Balance: Interpreting Climate Change Impacts Using a Water Balance Model

Dr. David Thoma, Ann Rodman, & Dr. Mike Tercek

In Yellowstone, the margin of life is thin but organisms adapted to the mountain environments survive. Long winters and short summers affect resource availability, and disturbances like fire pose other challenges to the persistence of Northern Range species like sagebrush, whitebark pine on Electric Peak, and boreal chorus frogs in a Mount Everts pond. Weather and climate are primary factors tipping the balance between the prosperity and demise of every species. These interactions have played out over thousands of years across a complex landscape and shape the remarkable patterns of floral and faunal biodiversity in Yellowstone today. But the climate is changing. Specifically, spatial and temporal patterns in temperature (T) and precipitation (P) are changing, but they are not changing the same way everywhere. Further complicating changes in climate are topographic factors like soil type and slope aspect that may buffer change at some locations but exacerbate change elsewhere. Additionally, effects are complicated by the different tolerances among species to extreme cold or drought conditions; survival and reproduction of sagebrush may be limited by moisture, whitebark pine may be limited by cold temperatures, and chorus frogs may be limited by both.

In the first issue of *Yellowstone Science*, Bill Romme and Monica Turner (Romme and Turner 1992) discussed possible influences of climate change on Yellowstone vegetation. They noted several future scenarios including hotter-drier, hotter-similar precipitation, and hotter-wetter conditions, and described how such changes could affect vegetation, fire regimes, and wildlife in Yellowstone. They used the terms "evapotranspiration," "water use efficiency," and "drought stress" in describing the forces that might affect vegetation, wildlife, and fire regimes. Now, more than 22 years later, with an

increasing awareness and growing need to understand the impacts of climate change, we use new data sets to explore the effects of changes in T and P on the Northern Range. Our research evaluated the interactions between T and P affecting timing and abundance of water in the environment and the biological communities that depend on water. Romme and Turner's prescient long-range scenarios covered a range of possible influences, all of which we cannot comment on here.

By focusing on the interaction of temperature and precipitation in this article we: 1) describe changes in P and T over the past few decades across the Northern Range, 2) explain how a water balance model integrates T and P in biophysically relevant ways, and 3) run the water balance model and discuss insights gained from exploring the interactions of T and P affecting timing, abundance, and fate of water in the environment with emphasis on evapotranspiration, drought stress, surface runoff, and growing degree days.

Change in the Weather

Which of Romme and Turner's three scenarios (hotter-drier, hotter-similar precipitation, hotter-wetter) have played out in recent decades? To answer this question,

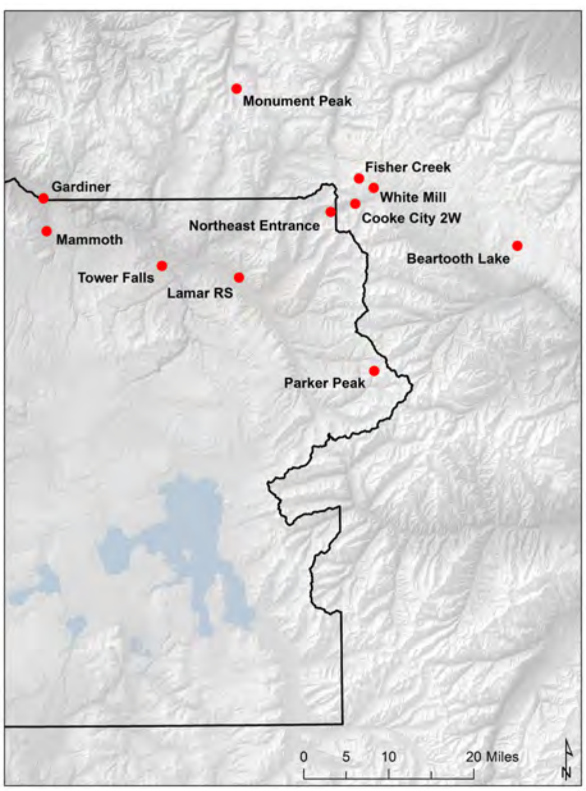


Figure 1. Northern Range weather station locations used in this research. Dark gray colors represent higher elevations.

we focused on 11 locations across the Northern Range to explore the variation and trends in weather (principally T and P) since 1980 (figure 1). We used daily values from the DAYMET gridded climate data set (Thornton et al. 2012) which is constructed from weather station data. It is important to note that our findings reflect spatial and temporal patterns in the DAYMET gridded climate data set. Results would differ slightly if we used different climate data sets such as PRISM or TopoWx. Furthermore, it is necessary to periodically reanalyze newly available climate data as the science of climate modeling matures and as our understanding of climate as a driver of biophysical process grows.

Our analyses show all elevations across the Northern Range warmed significantly (between 0.5-0.8°F/decade, figure 2). Elevations below 6,500 ft. also became significantly drier since 1980 (-1.2 in/decade) while elevations above 6,500 ft. show no significant trend in precipitation since 1980. These decadal rates of change for a relatively recent window of time are much greater than the century-long rates reported by Chang (this issue). This difference is a result of a shorter and relatively recent period of analysis, as well as a more limited analysis area (Northern Range). Climate summaries over longer periods of time and across larger areas tend to mask local extremes. However, understanding change at both scales is important for different research and management needs.

Some of the changes in climate we found on the Northern Range are statistically significant, but are they biologically relevant? That is, are the observed changes in T and P causing measurable changes in plants and animals? Answering that question requires coupling observations of climate with observations of change on the ground over time, an active area of research which is reported by others in this issue. In what ways might we expect increasing T and decreasing P to affect plants at low elevations, and how might increasing T without increasing P affect vegetation at high elevations? Does the interaction between T and P affect wetland dynamics differently at different elevations? It gets very confusing. So we use a water balance model to provide quantitative insight to these complicated questions.

A Water Balance Model

Water balance models of varying complexity have been around since the 1940s and are used extensively in agriculture for irrigation scheduling and for tracking drought across large areas (Federer et al. 1996, Hay and McCabe 2002). Since then water balance models have been used in wildland applications as well. Scientists recognized the water balance models provide a better representation of biophysical aspects of climate that affect plants, animals, and hydrology (Gray and McCabe 2010, Lutz et al. 2010, Stephenson 1998). By tracking where water goes after it falls from the sky, water balance models describe how T and P affect timing and abundance of water in the environment. The water balance model essentially "converts" measures of T and P into the more direct effects felt by plants and animals.

We used a model running on a monthly time step. This particular model was used in Yellowstone to model river runoff, and in Yosemite to demonstrate climatic influences on tree species distributions (Dingman 2008, Gray and McCabe 2010, Lutz et al. 2010). In the model, precipitation falls as either rain or snow that is stored in the snowpack until spring temperatures warm sufficiently to melt the accumulated snow (figure 3). Water can then take a few different paths. It can infiltrate underlying soil, where some is stored or passed through to resupply groundwater, or it can runoff (RO) to streams and lakes. Water stored in soil is used by plants for nutrient transport and carbon assimilation (i.e., photosynthesis) in a process called transpiration. The combined loss from plants (transpiration) and from soil surface (evaporation) is referred to as evapotranspiration (ET). When plants experience water stress, they close stomata and growth slows. Water deficit (D), a term similar to drought stress, represents the amount of water that could have been used by plants if it were available; it is the unmet evaporative demand. Growing degree days (GDD) are calculated from T as the biologically important duration of temperature above freezing. That is, GDD represents the amount of time T is suitable for biological growth. The "plants" in the model are theoretical and are similar to a green lawn in the real world. For this reason estimates coming from the model reflect relative differences and not actual differences that could be estimated by more sophisticated models which account for actual variation in vegetation types.

There are many applications for water balance studies; but we focus on estimating ET, D, RO, and GDD because these factors describe the timing of hydrologic events (e.g., peak flows), vegetation phenology, soil moisture, and water abundance and its persistence on the landscape. Evapotranspiration and D are strongly correlated with vegetation condition and distribution of vegetation habitats (Lutz et al. 2010, Stephenson 1998). Runoff, the water in excess of soil moisture storage and used in ET, is water that fills Yellowstone's biologically rich wetlands. Combined, these annually recurring hydrologic cycles in ET, D, and RO affect biological, chemical, and physical processes that shaped and will continue to shape the Yellowstone ecosystem.

A New Biophysical Environment?

In this article we analyzed data from a relatively short 31-year period starting in 1980 and do not claim these rates of change are similar to past or future rates across the GYE (see Chang, this issue). Nevertheless the changes in T and P have cascading effects more easily understood from a biological and hydrological perspective when viewed through the lens of the water balance.

In Yellowstone's Northern Range since 1980, water balance modeling suggests a relative decrease in ET at low elevations and a relative increase at high elevations (figure 4a). The relative water deficit increased at low

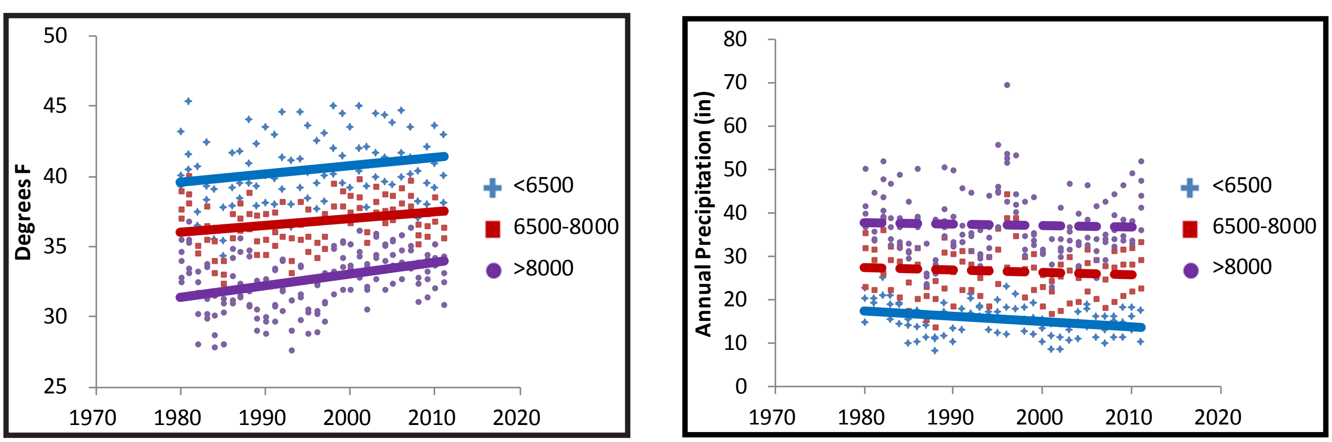


Figure 2. Variation and linear trends in annual mean temperature and annual precipitation at 11 weather stations on Yellowstone's Northern Range. Data are binned by elevation to demonstrate trends occurring at different rates at different elevations. Solid lines are statistically significant at $\alpha = 0.05$, while dashed lines are not statistically significant.

elevations, but had no change at mid or high elevations (figure 4b). The relative rate of RO decreased significantly at the lower elevations, but did not change significantly at mid or high elevations (figure 4c). Growing degree days increased significantly at high elevations (figure 4d).

These observations generally agree with other authors in this issue (Chang and Hansen et al.), but highlight the importance of place and timing of change across large elevation gradients. We highlight the biological importance of these differences by placing icons in the panels of figure 4 that represent plants and animals considered in this research that may be affected by changes in climate at different elevations. For instance, changes in ET and D at low elevations are likely to affect growing conditions for sagebrush and grass (figure 4a, 4b). Changes in RO at low elevations influence wetland hydroperiods which affect amphibians (figure 4c). Changes in growing degree days at high elevations are likely to affect amphibian development rates (tadpole icon) and growing conditions for whitebark pine (figure 4d). A closer inspection of monthly trends reveals most of these changes are happening in May through August which affects late summer river flow, vegetation water stress, and forest disease.

What does this mean to Yellowstone's biology? These complex changes are difficult to understand without quantitative models because biology and hydrology respond indirectly to T and P via interactions with slope, aspect, day length, solar angle, and soil properties. The water balance tells us sagebrush at lower elevations experienced more water stress due to increasing temperature and decreasing precipitation (figure 4a and 4b), while whitebark pine at higher elevations may have experienced wetter growing conditions on average since 1980 (figure 4a). The "wetter" condition at higher elevations was not caused by increased precipitation (figure 2), but by a warmer growing season lifting cold temperature limitations which previously prevented whitebark pine from using the available water (figure 4a, 4d). Warmer temperatures favored beetle reproduction which set the stage for the extensive whitebark pine mortality observed between 2007 and 2011 (Jewett et al. 2011, Logan et al. 2010, Shanahan et al. 2014). This highlights the role extreme modern events can play in affecting ecosystems. Extreme events are occurring more frequently in national parks across America (Monahan and Fisichelli 2014). Decreased precipitation at lower elevations resulted in less runoff, suggesting wetlands in these landscapes were less likely to fill and consequently be less reliable for chorus frog breeding (see Ray et al., this issue).

The magnitude of changes in T, P, ET, D, RO, and GDD since 1980 may not seem numerically large; but the importance of change is masked by the fact that changes in annual average conditions can occur due to either small but persistent changes or abrupt extremes in the biophysical environment. Persistence of either case may represent new conditions falling outside the range tolerated by species in their existing environments.

Implications

Changes in T and P since 1980 do not necessarily reflect long-term climate trends and may even represent an anomalous period of exceptionally rapid change (Hansen et al. 2012). However, these changes are consistent with projections for the Yellowstone region where temperatures may be 5-7°F warmer and precipitation may in-

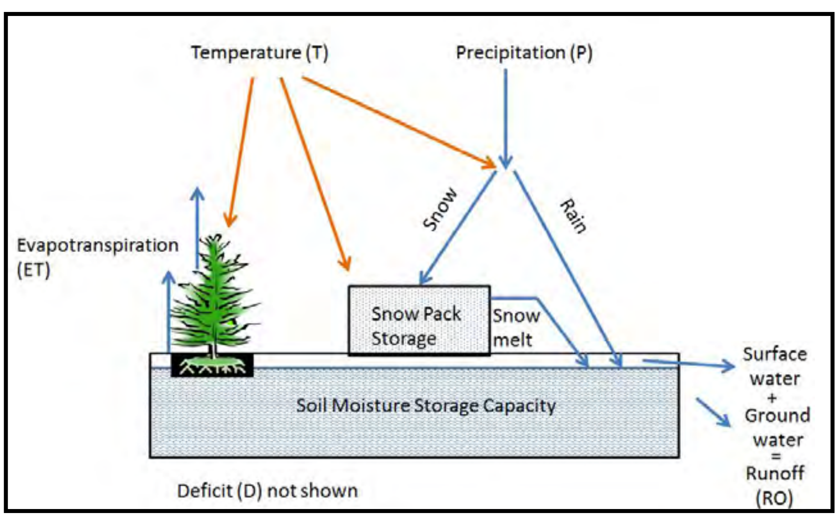


Figure 3. Conceptual diagram of temperature and precipitation interactions modeled by the water balance.

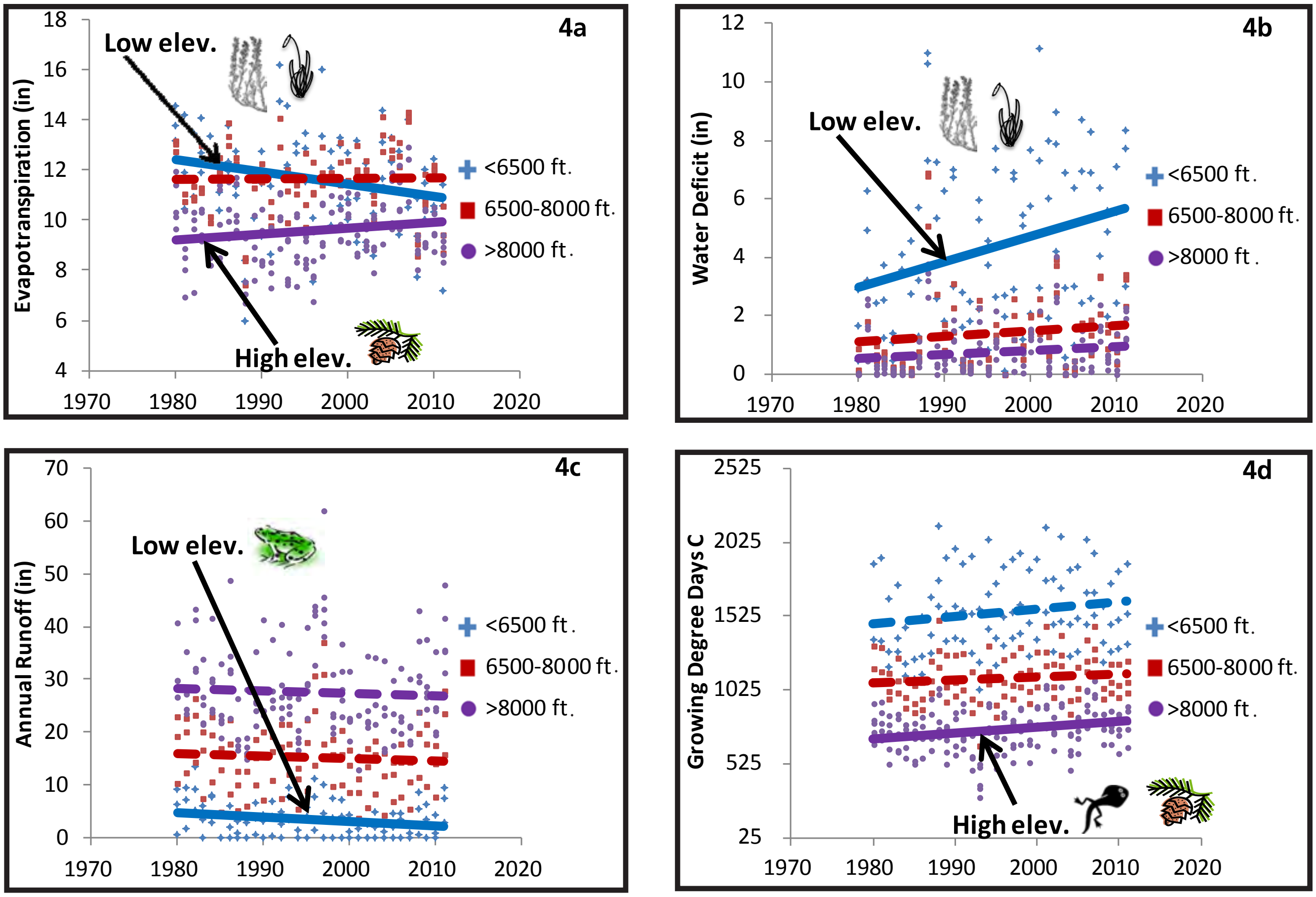


Figure 4. Annual variation and trends in evapotranspiration, deficit, runoff, and growing degree days at 11 weather station locations on the Northern Range. Solid lines are statistically significant at α = 0.05, while dashed lines are not statistically significant. The icons suggest biological effects of the different biophysical parameters on vegetation or amphibians at different elevations. [Sagebrush icon courtesy of USDA-NRCS PLANTS database.]

crease 5-8% by 2100 (Source: PRISM climate data, Tabor and Williams 2010 projections). These rates of change over the next 100 years are similar to changes in climate that resulted in dramatic reorganization of vegetation assemblages since deglaciation approximately 14,000 years ago (Barnosky 1992, Huerta et al. 2009, Pierce et al. 2003, Whitlock and Bartlein 1993).

We do not know how competition, disease, opportunistic establishment, predation, fire, or grazing might play out under these scenarios; but it is clear climate has changed as outlined by Romme and Turner (1992) in ways consistent with the hotter-drier scenario at lower elevations and the hotter-similar precipitation scenario at higher elevations. Under a hotter-drier scenario, forest and grassland biomes would shift upslope and semidesert vegetation would move into the lowest areas of Yellowstone (Romme and Turner 1992). At the higher elevations (> 8,000 ft.), P has been highly variable, but shows no significant trend. So in the case of temperature-limited high elevations, warmer spring-time temperatures may stimulate earlier snow melt and growth that result in earlier and more prolonged drought stress later in the growing season. High elevation warming may stimulate growth as suggested by modeled increases in ET and GDD, due to longer growing seasons, warmer growing seasons, or both. These changes may improve the competitive advantage of lower elevations species, enabling encroachment into higher elevation habitats formerly unfavorable (Whitlock and Bartlein 1993).

Not all vegetation shifts would be upslope. Deficit changes may cause upward shifts on south-facing low elevation slopes; whereas changes on north aspects, buffered from solar heat by topography, may be slower. Soils also play a role as species may find refuge and remain longer under changing T and P, especially in areas where change is moderated by greater local water availability via greater soil moisture storage. Thus some shifts may be to different aspects or to soils of different texture where the shift represents the change in location needed to maintain a similar biophysical environment to which species are adapted. Water balance models dramatically reduce the complexity in understanding the interactions of climate and landscapes by telling us how changes in T and P pressure biological responses through time and vary by geographic location.

Gradual and abrupt changes in climate should be considered when designing monitoring and research to assess the impacts of changes in biophysical factors. We now routinely track these types of change in climate data and have the opportunity to link climate observations to biological and physical response in ways that improve our ability to predict outcomes.

An interesting finding from this research was the indication that the same forces are not playing out uniformly across the Northern Range as evidenced by warmer-drier trends at low elevations, and warmer-similar precipitation at high elevations. Middle elevations have warmed, but no significant change in ET, D, RO, or GDD has been noted for this time period. However, if some of the biophysical conditions are changing rapidly above and below middle elevations, the expectation of significant change in middle elevations is likely to become evident over time. The occurrence of different processes limiting species' distributions and operating at different elevations highlights the importance of long-term climate data sets and the ability to evaluate these data in a geographic context as illustrated by this article and authors in this issue. Both spatial and temporal patterns must be carefully considered to understand climate forces affecting Yellowstone's biology and hydrology.

Conclusions

Over two decades have passed since Romme and Turner insightfully wrote on possible future climate scenarios in Yellowstone and how those conditions may affect vegetation, wildlife, and fire regimes. We described a warming trend at all elevations and a warming and drying trend at low elevations for a recent 31-year period on Yellowstone's Northern Range. Both scenarios were discussed by Romme and Turner, but it may be surprising that the patterns of change in T and P are not uniform across the landscape of the Northern Range. Today, our access to better climate data and tools for analysis creates opportunities to explore the biophysical relevance of landscape and climate interactions. Improving our ability to forecast future climate conditions and impacts is just one piece of the myriad types of information needed to manage natural resources under climate change.

In Yellowstone, the future of many organisms and habitats is uncertain. As we continue to collect more accurate and complete weather records, and as our models and conceptual understanding of climate as a prinicipal driver of species distributions and biological assemblages improves, we will be better enabled to mitigate, adapt, and respond to climate change in meaningful ways.

Literature Cited

Barnosky, E. 1992. Confidence in the past. Yellowstone Science 1(1):10-15.

Dingman, S.L. 2008. Physical Hydrology, second edition. Prentice Hall, Upper Saddle River, NJ, USA.

Federer, C.A., C. Vörösmarty, and B. Fekete. 1996. Intercomparison of methods for calculating potential evaporation in regional and global water balance models. Water Resources Research 32(7):2315-2321.

Gray, S.T., and G.J. McCabe. 2010. A combined water balance and tree ring approach to understanding the potential hydrologic effects of climate change in the central Rocky Mountain region. Water Resources Research 46(5):1-13.

Hansen, J., M. Sato, and R. Ruedy. 2012. Perception of climate change. Proceedings of the National Academy of Sciences 109(37):1-9.

Hay, L.E., and G.J. McCabe. 2002. Spatial variability in water-balance model performance in the conterminous United States. Journal of the American Water Resources Association 38(3):847-860.

Huerta, M., C. Whitlock, and J. Yale. 2009. Holocene vegetation-fire-climate linkages in northern Yellowstone National Park, USA. Palaeogeography, Palaeoclimatology, Palaeoecology 271:170-181.

Jewett, J.T., R.L. Lawrence, L.A. Marshall, P.E. Gessler, S.L. Powell, and S. Savage. 2011. Mortality in the Greater Yellowstone Ecosystem. Forest Science. 57(4):320-335.

Logan, J.A., W.W. MacFarlane, and L. Wilcox. 2010. Whitebark pine vulnerability to climate-driven mountain pine beetle disturbance in the Greater Yellowstone Ecosystem. Ecological Applications 20(4):895-902.

Lutz, J.A., J.W. van Wagtendonk, and J.F. Franklin. 2010. Climatic water deficit, tree species ranges, and climate change in Yosemite National Park. Journal of Biogeography 37(5):936-950.

Monahan, W.B., and N.A. Fisichelli. 2014. Climate exposure of US national parks in a new era of change. PLoS ONE 9(7):2-13.

Pierce, K.L., D.G. Despain, C. Whitlock, K.P. Cannon, G. Meyer, L. Morgan, and J.M. Licciardi. 2003. Quaternary geology and ecology of the Greater Yellowstone area. Pages 313-344 in D.J. Easterbrook, editor. Quaternary Geology of the United States, INQUA 2003 Field Guide Volume. Desert Research Institute, Reno, NV, USA.

Romme, W.H., and M.G. Turner. 1992. Global climate change in the Greater Yellowstone Ecosystem. Yellowstone Science 1(1):2-5.

Shanahan, E., K.M. Irvine, D. Roberts, A. Litt, K. Legg, and R. Daley. 2014. Status of whitebark pine in the Greater Yellowstone Ecosystem: A step-trend analysis comparing 2004-2007 to 2008-2011. Natural Resource Technical Report NPS/GRYN/NRTR—2014/917. National Park Service,Fort Collins, Colorado.

Stephenson, N.L. 1998. Actual evapotranspiration and deficit : Biologically meaningful correlates of vegetation distribution across spatial scales. Journal of Biogeography 25(5):855-870.

Tabor, K., and J.W. Williams. 2010. Globally downscaled climate projections for assessing the conservation impacts of climate change. Ecological Applications 20(2):554-565.

Thornton, P.E., M.M. Thornton, B.W. Mayer, N. Wilhelmi, Y. Wei, R. Devarakonda, and R.B. Cook. 2012. Daymet: Daily surface weather on a 1 km grid for North America, 1980-2012. Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. http://daymet.ornl.gov/ (accessed March14, 2013).

Whitlock, C., and P.J. Bartlein. 1993. Spatial variations of Holocene climatic change in the Yellowstone region. Quaternary Research 39(2):231–238.

YS

David Thoma, see page 27.

Ann Rodman, see page 5.

Mike Tercek, see page 27.

Photo by Bradley Orsted ©

Changing Climate Suitability for Forests in Yellowstone & the Rocky Mountains

Dr. Andrew Hansen, Dr. Nate Piekielek, Tony Chang, & Linda Phillips

How might the past and projected future changes in climate influence vegetation communities across the Greater Yellowstone Ecosystem (GYE) and the surrounding Rocky Mountains? This question is difficult to answer because of the complex interactions between climate and plant populations. Changes in climate will likely have direct effects on rates of establishment, growth, and death of plant populations. They will also have indirect effects via influence on other factors that interact with plant populations such as disturbance regimes (e.g., fire), pests (e.g., mountain pine beetle), and interactions with other species, such as competition, facilitation, pollination, and dispersal. Scientists have some level of uncertainty about each of these potential direct and indirect effects of climate change on a given plant species. Consequently, analyses that consider all of these effects and interactions among them typically have levels of uncertainty that are too high to be very informative to resource managers (Huntley et al. 2010). An approach that is a reasonable first step for informing management is to represent projected changes in climate through the lens of the tolerances of plant species.

Controlling for other factors, plants tend to have viable populations in locations where climate conditions are within their range of tolerances for establishment, growth, survival, and reproduction. With this in mind, an approach termed "bioclimate envelope modeling" quantifies the climate conditions where a species is currently present and projects the locations of these climate conditions under future scenarios (Huntley et al. 1995, Pearson and Dawson 2003, Guisan and Thuiller 2005). More specifically, current presence of a species is assumed to be determined by climate in the context of disturbance, biotic interactions, and other factors that influence species distributions. The projected areas of suitable climate are prefaced on the assumption that the interactions with disturbance and other ecological factors continue as at the present time. This method allows inference about potential climate suitability for a species (controlling for other factors). While this approach does not necessarily predict where a species will occur in the future (Pearson and Dawson 2003), it does project one foundational filter of where a species could exist in the future—climate suitability (Serra-Diaz et al. 2014).

The results of bioclimate envelope studies are very useful to resource managers for identifying which species may be most vulnerable to climate change and for developing management strategies for these species (Hansen and Phillips 2015). Whereas managers cannot manipulate climate over large landscapes, they can manipulate other factors that influence plant population viability: establishment, genetic composition, interactions with other species, and disturbances. Knowledge of climate suitability is a critical first filter for deciding where to use management actions to protect, restore, or establish certain populations under climate change. Species identified as vulnerable based on climate suitability are candidates for additional research used in vulnerability assessments (Dawson et al. 2011), which are typically more expensive and/or have higher uncertainty than climate suitability analyses.

We summarize three bioclimate envelope modeling studies for tree species across the U.S. Northern Rockies and within the GYE (figure 1). Hansen and Phillips (2015) integrated the results of published studies dealing with western North America tree species to assess their climate suitabilities within the Rocky Mountains of Wyoming, Montana, and Idaho. The results provide a broader context for interpreting potential changes in the GYE. In order to improve on the published studies within the GYE, Piekielek et al. (in review), used the newest Intergovernmental Panel on Climate Change (IPCC) climate projections, drew on the abundant plant field data for the GYE, and included consideration of habitat factors in addition to climate, such as soil, water balance, and topography. Chang et al. (2014) focused on whitebark pine, the species found to be most vulnerable to changes in climate suitability in the Rocky Mountain analysis. This analysis used methods similar to Piekielek et al., but additionally examined the variability in climate suitability projected

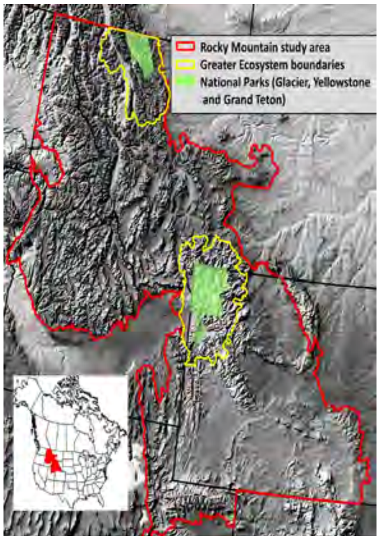


Figure 1. Climate suitability for vegetation was evaluated across the U.S. Northern Rockies (outlined in red) by Hansen and Phillips (2015) and within the Greater Yellowstone Ecosystem by Chang et al. (2014) and Piekielek et al. (in review). Modified from Hansen and Phillips 2015.

under different global circulation models (GCMs). These three studies all used two climate scenarios: a higher greenhouse gas emissions scenario termed A2 or RCP 8.5 in various IPCC iterations and a lower emissions scenario that assumes global reduction in the rate of emissions termed B1 or RCP 4.5 (IPCC 2007, Moss et al. 2008). We report the results of both sets of scenarios in this synthesis.

U.S. Northern Rockies

The four studies evaluated by Hansen and Phillips (2015) all projected substantial declines in climate suitability for subalpine tree species across the Northern Rocky Mountains. Averaging among the studies, the proportion of the study area with suitable climate for whitebark pine dropped from 21% currently to 8.8% by 2070-2100 under the B1 scenario and to 11% under the A2 scenario (figure 2). Remaining suitable climate area by 2100 for Engelmann spruce, subalpine fir, and lodgepole pine was 18-25% under B1 and 16-25% under A2. Among the montane species, ponderosa pine and grand fir climate suitable areas were projected to increase substantially. The studies disagreed on Douglas-fir, with some studies projecting expansion and others contraction. Among the tree species now found in the more mesic Rocky Mountain westslope, mountain hemlock was projected to decrease dramatically under both climate scenarios, while western red cedar and western hemlock were projected to increase moderately.

The spatial patterns of change in climate suitability projected for the next century help place the GYE in the context of the surrounding Rocky Mountains. Climate suitability for the subalpine species decreased on the westside of the Continental Divide and in lower elevations around the GYE. In contrast, Douglas-fir and especially ponderosa pine climate suitability were projected to expand throughout the westslope and in lower to mid-elevations of the GYE under both climate scenarios.

Four metrics derived from these climate suitability anaylses were used to rank vulnerability of the tree species. Whitebark pine and mountain hemlock had the highest vulnerability scores (figure 3). These species and the other subalpine species (Engelmann spruce, subalpine fir, and lodgepole pine) were placed in the high vulnerability class because of the large decline in projected suitable area and low gain in newly suitable areas. Western hemlock, western redcedar, western larch, and Douglas-fir were considered medium in vulnerability. Ponderosa pine and grand fir were projected to gain substantially in area of suitable habitat and were considered low in vulnerability.

Greater Yellowstone Ecosystem

To what extent do more detailed habitat models for the GYE confirm or differ from the Rocky Mountain climate suitability projections described above? Piekielek et al. (in review) found subalpine species declined dramatically in projected areas of suitable habitat by 2099 under RCP 4.5 (50-77% decrease) and RCP 8.5 (80-90% decrease) (table 1). The montane species aspen, Douglas-fir, and lodgepole pine also showed substantial decreases in suitable habitat area with decreases of 10-53% under RCP 4.5 and decreases of 60-85% under RCP 8.5. Some lower treeline communities were projected to increase substantially in suitable habitat. The juniper community type was projected to increase 32% and 55% in suitable habitat area under RCP 4.5 and RCP 8.5, respectively. The sagebrush community was projected to increase 31% and 40% in suitable area under the two scenarios.

The habitat variables that consistently contributed to the best habitat models included early growing-season snowpack, late season soil water-deficit, mid-season soil moisture, and soil texture. These predictors are consistent with hypotheses on factors that limit tree species in the GYE and indicate that consideration of water balance and soil are improvements on models that only consider climate.

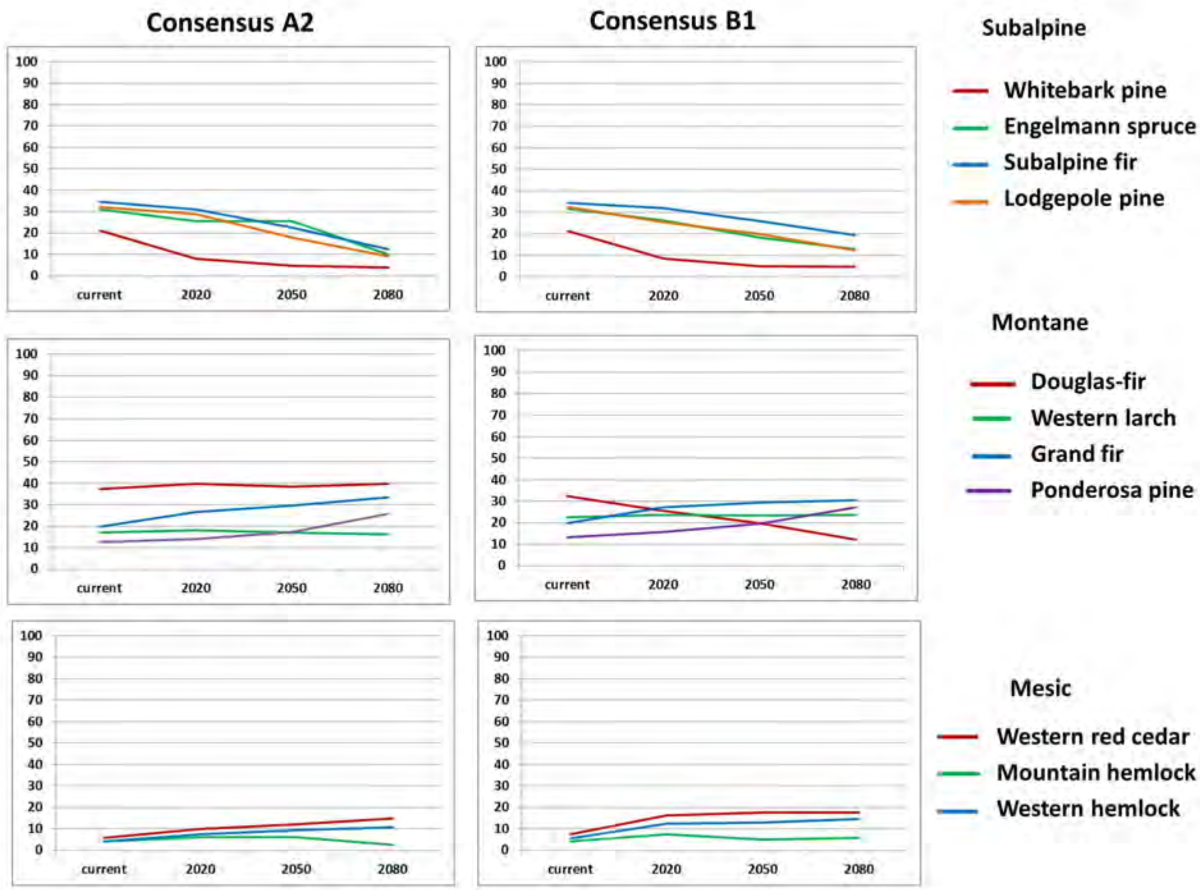


Figure 2. Projected change in the proportion of the Northern Rockies study area with suitable climate for each tree species averaging the results of the four studies considered in Hansen and Phillips (2015) under the A2 and B1 climate scenarios.

Maps of projected changes in climate suitability illustrate sagebrush and juniper communities, now at the warmer and drier lower forest treeline, expanding by 2100 onto the mid-elevations of the Yellowstone Plateau (e.g., figure 4). Douglas-fir was projected to contract from current mid- to lower elevation settings and expand onto the Yellowstone Plateau under RCP 4.5 but not RCP 8.5. Lodgepole pine was projected to continue to have suitable habitat on the Yellowstone Plateau under both scenarios. Habitat suitability for subalpine fir and Engelmann spruce was projected to remain only in the highest elevations under both scenarios.

Whitebark pine is of special interest in GYE. It is considered a keystone species in the subalpine (Logan et al. 2010). It provides a food source for wildlife, including the grizzly bear. It also serves the ecosystem functions of stabilizing soil, moderating snow melt and runoff, and facilitating establishment by other conifer species. Whitebark pine has experienced a notable decline in the past decade due to high rates of infestation from the mountain pine beetle (*Dendroctonus ponderosae*) and infections from white pine blister rust (*Cronartium ribicola*) (Macfarlane et al. 2012). Furthermore, whitebark pine was found to have the highest vulnerability to climate change in the Rocky Mountain analysis described above.

Chang et al. (2014) found the presence of whitebark pine in the GYE was associated with lower summer maximum temperatures and higher springtime snowpack. Patterns of projected habitat change by the end of the century suggested a constant decrease in suitable area from a 2010 baseline. Among nine GCMs, percent suitable climate area estimates in 2100 averaged 16.5% and 3% of the 2010 baseline for RCP 4.5 and 8.5, respectively (figure 5). Projected suitable area for individual GCMs varied from 29-2% and 10-0.04% by 2099 for RCP 4.5 and 8.5, respectively, illustrating that GCMs differ in climate projections that are relevant to climate suitability projections for this species. However, the agreement among all the GCMs in substantial declines in whitebark pine climate suitability suggests a high level of concern for this species in GYE is warranted. Projected suitable habitats for this species by 2100 are only in the highest elevations of the GYE, largely on the Beartooth Plateau, the Absaroka Range, and the Wind River Range.

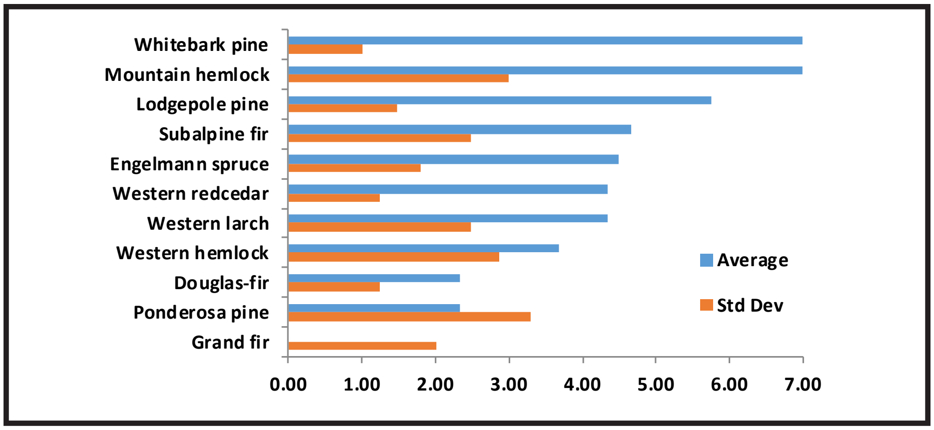


Figure 3. Results of vulnerability assessment ranking averaged among studies under the A2 scenario. From Hansen and Phillips (2015).

Table 1. Percent change in projected area of suitable habitat across the GYE in 2040, 2070, and 2100 under two climate scenarios. From Piekielek et al. (in review).

Common Tree Species Name	RCP 4.5			RCP 8.5		
	2040	2070	2100	2040	2070	2100
Sagebrush	17	23	31	18	28	40
Juniper	18	26	32	16	32	55
Limber pine	-13	-8	-22	-15	-37	-29
Aspen	-1	-5	-10	7	-1	-60
Douglas-fir	-35	-38	-53	-37	-63	-73
Lodgepole pine	-28	-42	-50	-26	-53	-85
Engelmann spruce	-46	-61	-77	-47	-77	-90
Supalpine fire	-43	-56	-68	-44	-66	-80

Implications for Research and Management

The results of the three studies described above suggest the climate suitability for forests of the GYE will change substantially in the coming century. The warming temperatures, decreasing springtime snowpack, and decreasing late season soil moisture projected by the GCMs would result in a longer, warmer, and drier growing season than present. In general, vegetation types are projected to shift upward in elevation. Sagebrush and juniper communities are projected to expand from valley bottoms upslope into the lower forest zone and the Yellowstone Plateau. Climate suitability for the dense and productive Douglas-fir and aspen forests now in the lower forest zone is projected to deteriorate for these species. Ponderosa pine, a species not currently found in the GYE, is projected to have suitable habitat in this zone by the end of the century.

Projections for the Yellowstone Plateau, which occupies the central portion of Yellowstone National Park, are complex; and vegetation patterns there are further complicated by soils. The coarse textured and nutrient poor rhyolitic soils on the plateau are thought to currently limit the distribution of Douglas-fir and aspen on the plateau (Despain 1990), and this may continue to be the case even if climate becomes more suitable for these species. Given that the Yellowstone Plateau is projected to provide suitable habitats for sagebrush, juniper, and lodgepole pine, the actual distributions of these species are likely to be governed by disturbance and other ecological factors. Subalpine species are projected to have reduced climate suitability in much of their current range, while higher elevations become more suitable in climate for these species. Many of these high-elevation locations, however, are now dominated by rock, which will likely constrain the area of suitable habitat for these species.

Given the projected changes in habitat suitability described above, a number of questions arise as to the consequences for vegetation of the indirect effects of climate change. How will climate change influence fire regimes, and what will be the consequences for vegetation patterns? Based on climate change alone, fire frequency was projected to increase dramatically across all elevations of the GYE (Westerling et al. 2011). How will change in climate influence forest pests? Buotte et al. (in review) project increasingly favorable climate conditions for mountain pine beetles. How will changes in forest habitat suitability, fire regimes, and pest outbreaks interact to influence patterns of vegetation across the GYE? We speculate these interacting factors will result in vegetation in GYE later in the century being dominated by nonforest communities and remaining forest communities being earlier in seral stage and lower in canopy cover.

Whitebark pine was projected to have the greatest loss in area of suitable habitat in the GYE. The areal extent of adult reproductive aged stands has already declined dramatically across the GYE due to mortality from mountain pine beetles (Logan et al. 2010). Will whitebark pine be entirely lost from the GYE? Hope for the persistence of whitebark pine in GYE is bolstered by its history. Pollen records indicate that five-needle pine (whitebark and/or limber pine) remained in the region over the past 10,000 years even during the relatively warm hypsithermal period (Iglesias et al., in revision). More research is needed, but various hypotheses suggest viable populations can remain through the projected harsher climate in 2100 (Hansen et al., in preparation):

• About 960 km^2 of suitable habitat is projected to remain, even under the more extreme RCP 8.5 scenario (Chang et al. 2014), possibly allowing the population to persist, albeit at a greatly reduced size. This projected suitable habitat is at the highest elevations in GYE and an unknown, but probably substantial portion of this is rock and unsuitable for the species.

• Some locations projected to become unsuitable may actually have small pockets that remain suitable due to microsite characteristics. Local steep, north-facing slopes may maintain cooler temperatures and later snowpack than projected by the 800-m climate data used in the climate suitability analyses. Such sites may serve as microrefugia (Dobrowski 2011), where whitebark pine is able to persist even while the surrounding landscape becomes unsuitable.

• Within the whitebark pine population, genetic variants may exist that are better able to tolerate more extreme climate conditions. These variants likely would be favored by selection as climate warms.

• The current distribution is thought to be strongly limited by competition with other conifer species, and the species may be able to persist in warmer conditions in

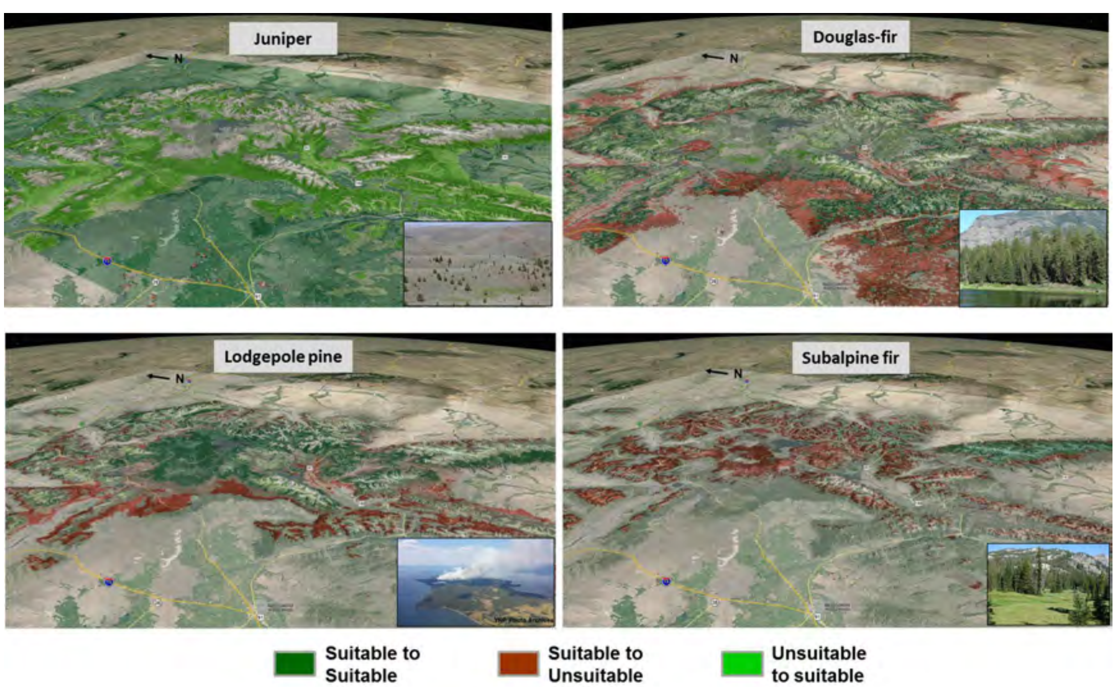


Figure 4. Oblique view from the southwest of the GYE showing change in modeled spatial distribution of climate suitable areas for tree species from the reference period to 2100 under the RCP 8.5 climate scenario based on majority agreement of nine GCM model runs. Data from Pielielek et al. (in review). Photos by A. Hansen and the YNP photo archive.

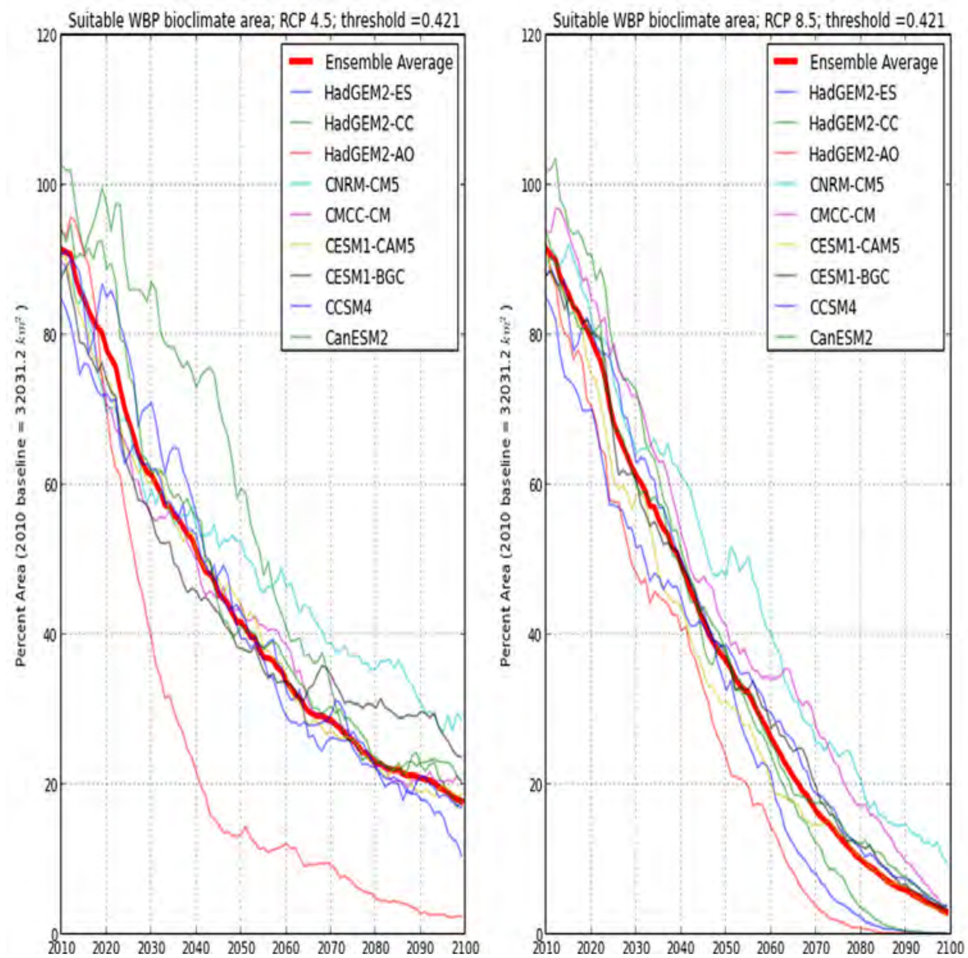


Figure 5. Bioclimate projections for whitebark pine for 2010 to 2099 under 30-year moving averaged climates under nine Global Climate Models for a moderate climate warming scenario (left) and a more extreme scenario (right). From Chang et al. (2014).

the absence of competition (GYCC 2011). This raises the possibility that active management to reduce competition from lodgepole pine and subalpine fir could favor whitebark pine under a changing climate.

• Some of the current mortality of this species is caused by white pine blister rust. Seedlings that are genetically resistant to the rust have been propagated and are being planted. If these seedlings are planted in locations projected to maintain suitable climate, competing vegetation is controlled, and mountain pine beetles do not cause mortality, these seedlings may contribute to the maintenance of a viable population.

The changes in the aerial extent of vegetation projected above would likely have large consequences for the provisioning of ecosystem services across the GYE. Loss of coniferous forest cover would likely further exacerbate reductions in snowpack due to warming spring temperatures, with large consequences for stream flows and temperature, cold-water fish populations, and downstream water availability for irrigation and human consumption. Habitat quality would be expected to deteriorate for the many species of wildlife now dependent on forest habitats and snow cover. Implications for the quality of visitor experiences and recreational opportunities are poorly understood.

Tools to Address Climate Change

Projected climate change represents a very significant challenge to natural resource managers. There is high uncertainty about the magnitude of climate change, the ecological response to it, the effectiveness of various management treatments, and even the appropriateness of active management in some wildlands. Fortunately, approaches are being developed and tested. "Climate adaptation planning" (e.g., Stein et al. 2014) involves multiple steps that link climate science and management. Research is used to project potential future response to climate change and reduce uncertainty. Monitoring in fast changing places provides information on actual rates of change and ecological response to this change. Vulnerability assessments can reveal which species or ecosystems are most at risk, where these are located, and why they are at risk. Education programs for natural resource staff and the public can help promote an understanding of the issues and for formulating effective policy. Agency planning documents can incorporate consideration of climate change in order to mitigate undesirable climate change impacts on projects. Passive management, such as allowing fires to burn, can sometimes favor species vulnerable to climate change. Finally, a variety of types of active management are being developed and evaluated aimed at protecting existing populations until newly suitable habitats develop, facilitating natural establishment in newly suitable habitats, and assisted migration to suitable areas.

There is currently much discussion and debate about the use of active management on some federal lands. The enabling legislation for restricted federal land types, such as national parks, roadless areas, and designated wilderness areas, encourage or require minimal human intervention (Long and Biber 2014). The three studies summarized above all found projected suitable habitat for vegetation increasingly shifts from unrestricted federal lands to the restricted federal lands which dominate the higher elevations. While the debate over active management in wildlands facing climate change will continue, it should be noted that research, monitoring, education, vulnerability assessment, and passive management are all viable options for managers of restricted federal lands.

"Assisted migration"

"Assisted migration" or managed relocation is the act of deliberately assisting plant or wildlife species to colonize new habitats. The method is intended to facilitate conservation of valued species by shifting populations to alternative areas that are predicted to be suitable habitat for these target species (IPCC Climate Change Synthesis Report 2014). The consequences of assisted migration have been subject to limited case studies. It is difficult to predict the ultimate success, or failure, of assisted migration or the unintended impacts to native flora and fauna from the introduction of species into new regions. However, the use of assisted migration as a climate change adaptation tool may be a viable option for several species in the GYE, such as whitebark pine.

Literature Cited

Buotte, P.C., J.A. Hicke, H.K. Preisler, J.T. Abatzoglou, K.F. Raffa, and J.A. Logan. In review. Historical and future climate influences on mountain pine beetle outbreaks in whitebark pine forests of the Greater Yellowstone Ecosystem. PNAS.

Chang, T., A.J. Hansen, and N. Piekielek. 2014. Patterns and variability of projected bioclimatic habitat for *Pinus albicaulis* in the Greater Yellowstone Area. PLoS ONE 9(11):e111669.

Dawson, T.P., S.T. Jackson, J.I. House, I.C. Prentice, and G.M. Mace. 2011. Beyond predictions: Biodiversity conservation in a changing climate. Science 332(6025):53-58.

Despain, D.G. 1990. Yellowstone vegetation: Consequences of environment and history in a natural setting. Roberts Reinhart Publishers, Boulder, CO.

Dobrowski, S.Z. 2011. A climatic basis for microrefugia: The influence of terrain on climate. Global Change Biology 17(2):1022-1035.

Guisan, A., and W. Thuiller. 2005. Predicting species distribution: Offering more than simple habitat models. Ecology Letters 8(9):993-1009.

GYCC. 2011. Whitebark pine strategy for the Greater Yellowstone Area. Greater Yellowstone Coordinating Committee Whitebark Pine Subcommittee.

Hansen, A.J., and L.B. Phillips. 2015. Which tree species and biome types are most vulnerable to climate change in the US Northern Rocky Mountains? Forest Ecology and Management 338:68-83.

Hansen, A.J., E. Barge, K. Ireland, M. Jenkins, M. Pillet, and K. Legg. In preparation. Population viability under deteriorating climate: Exploring "windows of opportunity" for whitebark pine in greater Yellowstone. Ecological Applications.

Huntley, B., P.M Berry, W. Cramer, and A.P. Mcdonald. 1995. Modeling present and potential future ranges of some European higher plants using climate response surfaces. Journal of Biogeography 22:967-1001.

Huntley, B., P. Barnard, R. Altwegg, L.Chambers, B.W.T. Coetzee, L. Gibson, P.A.R. Hockey, D.G. Hole, G.F. Midgley, L.G. Underhill, and S.G. Willis. 2010. Beyond bioclimatic envelopes: Dynamic species' range and abundance modelling in the context of climatic change. Ecography 33(3):621-626.

Iglesias, V., T.R. Krause, and C. Whitlock. In revision. Complex response of pine to past environmental variability increases understanding of its future vulnerability. PLoS ONE.

IPCC. 2007. Climate change 2007: Synthesis report. Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Logan, J.A., W.W. Macfarlane, and L. Willcox. 2010. Whitebark pine vulnerability to climate-driven mountain pine beetle disturbance in the Greater Yellowstone Ecosystem. Ecological Applications 20(4):895-902.

Long, E., and E. Biber. 2014. The Wilderness Act and climate change adaptation. Environmental Law 44:623-684.

Macfarlane, W.W., J.A. Logan, and W. Kern. 2012. An innovative aerial assessment of greater Yellowstone ecosystem mountain pine beetle-caused whitebark pine mortality. Ecological Applications 23(4):421–437.

Moss, R.H., M. Babiker, S. Brinkman, E. Calvo, and T. Carter. 2008. Towards new scenarios for analysis of emissions, climate change, impacts, and response strategies. Nature 463:747-756.

Pearson, R.G., and T.P. Dawson. 2003. Predicting the impacts of climate change on the distribution of species: Are bioclimate envelope models useful? Global Ecology and Biogeography 12(5):361-371.

Piekielek, N., A.J. Hansen, and T. Chang. In review. Projected changes in seasonal water-balance suggest decline in climate suitability for forest species in the Greater Yellowstone Ecosystem. Journal of Biogeography.

Serra-Diaz, J.M., J. Franklin, M. Ninyerola, F.W. Davis, A.D. Syphard, H.M. Regan, and M. Ikegami. 2014. Bioclimatic velocity: The pace of species exposure to climate change. Diversity and Distributions 20(2):169-180.

Stein, B.A., P. Glick, N. Edelson, and A. Staudt. 2014. Climate-smart conservation: Putting adaptation principles into practice. National Wildlife Federation, Washington, D.C.

Westerling, A.L., M.G. Turner, E.A. Smithwick, W.H. Romme, and M.G. Ryan. 2011. Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. Proc Natl Acad Sci 108(32):13165-13170.

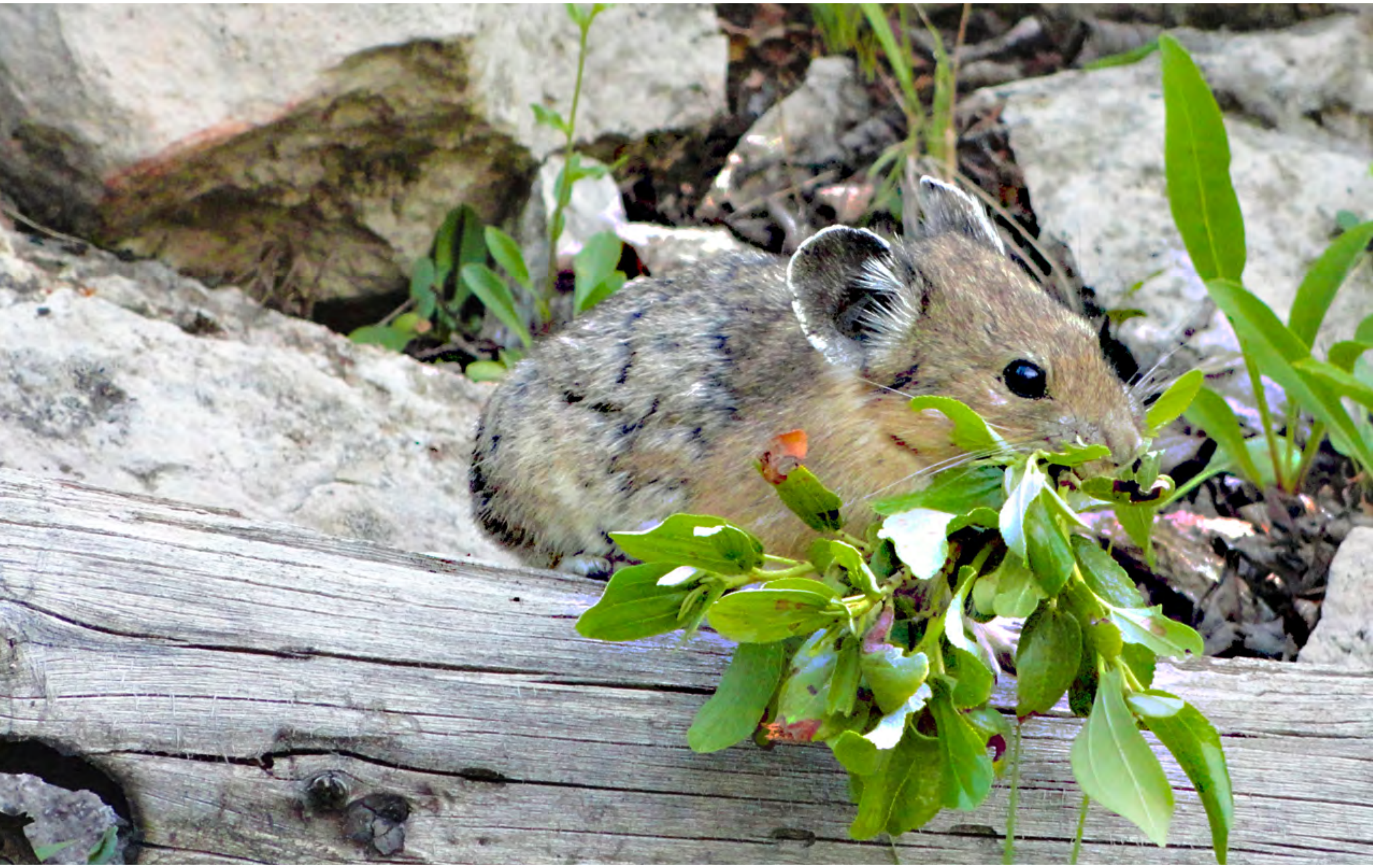
YS

Andrew Hansen see page 19.

Nathan Piekielek is the Geospatial Services Librarian at Pennsylvania State University. He works in the University Libraries Research Hub where he supports the use of geospatial technologies across the university. Prior to his current position, he worked for and with the National Park Service for over 10 years, including as a Post Doctoral Research Associate and graduate student in the Ecology Department at Montana State University.

Tony Chang, see page 19.

Linda Phillips is a Research Scientist and Spatial Analyst who has worked in the Ecology Department at MSU for 14 years. She specializes in the spatial database development and analysis of projects for the Landscape Biodiversity Lab.



Monitoring Greater Yellowstone Ecosystem Wetlands: Can Long-term Monitoring Help Us Understand Their Future?

Dr. Andrew Ray, Dr. Adam Sepulveda, Dr. Blake Hossack, Debra Patla, Dr. David Thoma, Dr. Robert Al-Chokhachy, & Dr. Andrea Litt

Photo 1. Wetlands near Cygnet Lakes Trail off Norris Canyon road.

In the Greater Yellowstone Ecosystem (GYE), changes in the drying cycles of wetlands have been documented (McMenamin et al. 2008, Schook 2012). Wetlands are areas where the water table is at or near the land surface and standing shallow water is present for much or all of the growing season (photo 1). We discuss how monitoring data can be used to document variation in annual flooding and drying patterns of wetlands monitored across Yellowstone and Grand Teton national parks, investigate how these patterns are related to a changing climate, and explore how drying of wetlands may impact amphibians. The documented declines of some amphibian species are of growing concern to scientists and land managers alike, in part because disappearances have occurred in some of the most protected places (Corn et al. 1997, Drost and Fellers 1996, Fellers et al. 2008). These disappearances are a recognized component of what is being described as Earth's sixth mass extinction (Wake and Vredenburg 2008).

In Yellowstone and Grand Teton national parks, depressional wetlands (i.e., those lacking flowing water, including ponds, wet meadows, and marshes bordering lakes and rivers) are the most prevalent wetland type and constitute approximately 3% of the landscape (Gould et al. 2012). Despite limited representation, 38% of all of Yellowstone's 1,200 documented plants species and 70% of Wyoming's 400 bird species are associated with wetlands (Elliot and Hektner 2000, Nicholoff 2003). Wetland-associated birds include obligate species (e.g., trumpeter swans and sandhill cranes) and upland-nesters that use wetlands for feeding (e.g., tree swallows). All five native species of amphibians (boreal chorus frogs, boreal toads, Columbia spotted frogs, plains spadefoot, and western tiger salamanders) occurring in Yellowstone are dependent on wetlands for breeding. Many of Yellowstone's mammals live in or regularly use wetlands (e.g., beavers, muskrats, otters, and moose). Aquatic invertebrates and wetland-breeding insects provide critical food resources for many species of wildlife.

Freshwater wetlands are equally important outside of this region, covering approximately 4% of the Earth's surface (Prigent et al. 2001). Worldwide, wetlands provide crucial habitat for a diversity of plants and animals, function as carbon sinks, and are widely used for outdoor recreation. Wetlands are often described as "keystone habitats" because their influence on ecosystem function and structure is disproportional to their size. Despite their natural value, wetlands have been drained, filled, or manipulated by humans for centuries (Mitsch and Gosselink 2007, Zedler and Kercher 2005). Over half of the wetland acres in the conterminous United States have been lost since 1780, including > 25% in Montana and nearly 40% in Wyoming (Dahl 1990). Because of these historic and widespread losses, wetlands in the United States are protected under the Clean Water Act. Even with current regulatory protections, low-elevation wetlands in Wyoming are still vulnerable to land use and climate change (Copeland et al. 2010).

Although periodic and regular drying is an important component of most wetland ecosystems (Prigent et al. 2001), a recent report by the International Panel on Climate Change (IPCC) stated wetlands and shallow ponds are among the most vulnerable to changes in climate (IPCC 2008). Many wetland-dependent species have adaptations allowing them to cope with these highly variable environments (Williams 1997), but permanent drying of wetlands or significant changes in flooding patterns could cause profound changes to productivity and biodiversity across the globe and throughout Yellowstone and Grand Teton national parks (Copeland et al. 2010, Junk et al. 2006, Ray et al. 2014).

Amphibian Monitoring in the Greater Yellowstone Ecosystem

Annual amphibian monitoring has been conducted in the wetlands of Yellowstone and Grand Teton national parks since 2000 by the NPS Greater Yellowstone Inventory and Monitoring Network, the U.S. Geological Survey's Amphibian Research and Monitoring Initiative, university and non-governmental cooperators (Gould et al. 2012). The parks were divided into 3,370 catchments, or discrete land units connected by surface water flows,

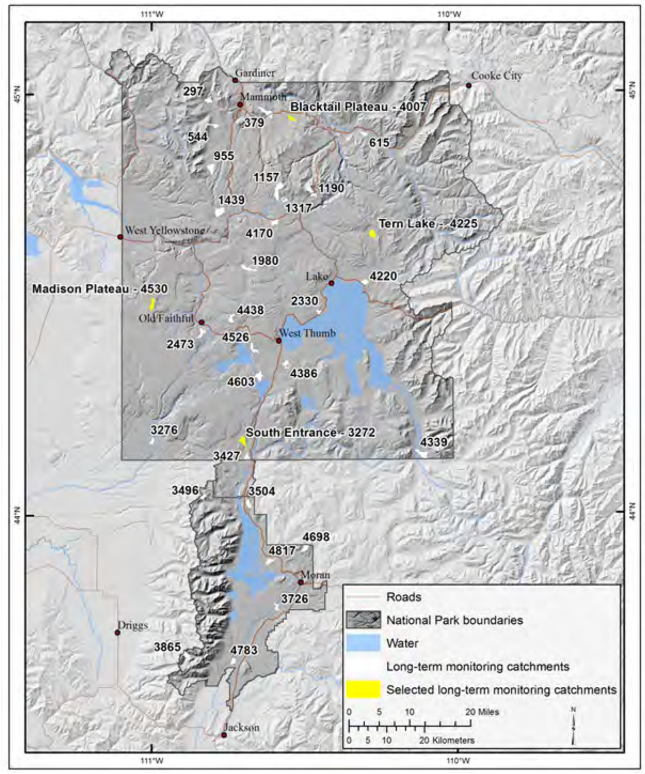


Figure 1. Long-term monitoring catchments in Yellowstone and Grand Teton national parks where annual wetland visits occurred and amphibian surveys were completed.

averaging 200 hectares (approximately 495 acres) in size. A random subset of catchments across both parks was selected to serve as the basis for long-term monitoring (figure 1). Wetlands within these catchments were visited annually in mid-summer. During the annual field visit, amphibian surveys were conducted; and size, depth, and vegetative coverage were documented.

To understand how observed variation in wetland flooding affects amphibians and other wetland-dependent taxa, we examined the relationships between weather data, surface runoff, and wetland inundation from 2005 to 2012 (figure 2). Wetland inundation is the presence of surface water observed during annual summer surveys. Sites without surface water were described as 'dry', while sites with even a minimal expanse of surface water were described as 'inundated'. Generally, the amount of surface water on the landscape that is available to fill or inundate wetlands and support amphibian breeding is related to air temperature, precipitation, and site-specific characteristics like soil and topography. Higher air temperatures contribute directly to increased evaporation and soil drying; this in turn affects how much precipitation infiltrates the landscape and sustains wetlands.

Temperature and precipitation data were used in a water balance model (see Thoma et al., this issue) to calculate annual runoff (the amount of water available to fill wetlands after evaporation and other pathways are accounted for) using daily estimates in monthly time steps. Average maximum and minimum air temperatures, and average regional precipitation for calendar years 2005 to 2012 were compared to the 30-year average (1982–2012, figure 2). Maximum and minimum air temperatures both influence wetland inundation. Maximum temperatures have a greater influence on evaporation rates, desiccating soils and contributing to wetland drying, while minimum temperatures reveal important information about conditions important for maintaining snow. Snow is a critical source of water for wetlands located at high elevations (Corn 2003).

Amphibian monitoring records from 2005 through 2012 were compiled, and photographs were taken in the field to describe and document annual wetland inundation status. Additionally, we assessed the relationship between annual runoff and percentage of wetlands inundated across all catchments in Yellowstone and Grand Teton and for four catchments representing four geographically and hydrologically distinct regions of Yellowstone: the Northern Range (Blacktail Plateau), the Madison Plateau, the South Entrance, and the Tern Lake area (figure 1). Precipitation, air temperature, soil, and topography vary among these catchments; as a result, each watershed contains wetlands with different sensitivities to annual runoff.

Finally, we explored how annual variations in wetland inundation affected the occurrence of breeding boreal chorus frogs. Chorus frogs may be most vulnerable to wetland drying due to breeding habitat preference for seasonal pools, wet meadows, and shallow portions of permanent wetlands (Koch and Peterson 1995). Previous analyses of chorus frog breeding occurrence in the parks indicated a sharp reduction at both seasonal and permanent wetlands in the dry year 2007 (Gould et al. 2012).

Annual Runoff & Amphibian Occurrence

Maximum and minimum air temperatures since 2005 are generally warmer than the 30-year average, but minimum air temperatures exhibit the strongest departure from the longer-term average (figure 2a). Annual precipitation and annual runoff have varied around the 30-year average during this period (figure 2b and 2c). Notable among the monitoring years were 2007 and 2011. In 2007, maximum air temperatures were high, and precipitation

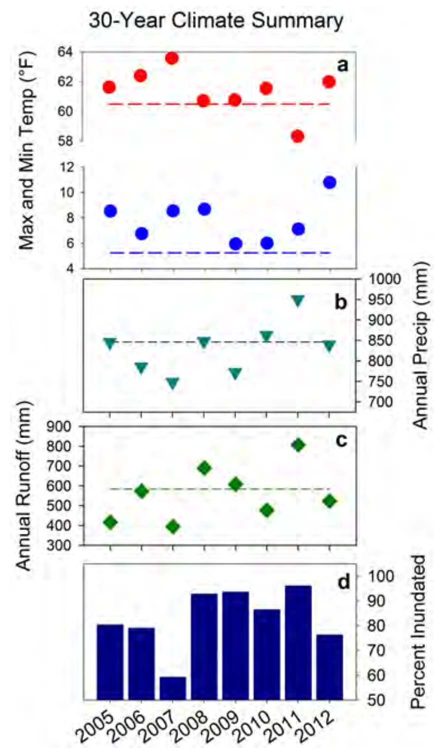


Figure 2. Summary of average annual maximum (red circles) and minimum (blue circles) air temperatures (a), total annual precipitation (b), total annual runoff (c), and the percentage of monitored wetlands inundated annually (d). Maximum and minimum air temperatures for years 2005 to 2012 are presented in degrees Fahrenheit (circles) and are shown along with the 30-year (1982-2012) average (dashed line) to highlight differences between a given year and the longer-term average. Similarly, 2005 to 2012 estimated annual precipitation (triangles) and runoff (diamonds) totals are shown along with the 1982-2012 average (dashed line) for each parameter.

and runoff were low. Conversely, maximum air temperatures were low, and precipitation and runoff were high in 2011. The percent of monitored wetlands inundated also varied among years, with a lower percentage (59%) of wetlands inundated in 2007 and higher percentage (96%) inundated in 2011 (figure 2d).

Across all Yellowstone and Grand Teton national park catchments, a strong relationship between the amount of runoff per year and the number of inundated wetlands was found (figure 3) but varied by catchment. Percentage of wetlands inundated within catchments 3272 (South Entrance), 4530 (Madison Plateau), and 4007 (Blacktail Plateau) generally increased with available runoff, while the percentage of wetlands inundated in catchment Y4225 (Tern Lake area) appeared to be unrelated to annual runoff (figure 4).

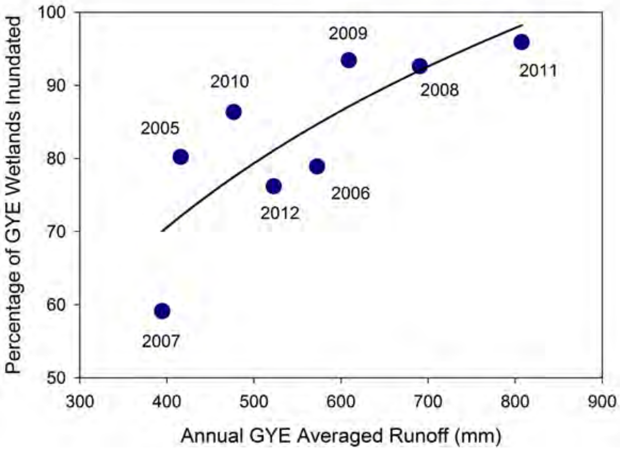


Figure 3. Percentage of monitored wetlands in Yellowstone and Grand Teton national parks (collectively GYE) inundated yearly and relationship to annual estimated runoff for the entire GYE in that same year. The relationship is statistically significant and explains nearly two-thirds of the variation documented in wetland flooding (R^2 = 0.65). GYE runoff estimates represent an average across all wetlands monitored in the GYE.

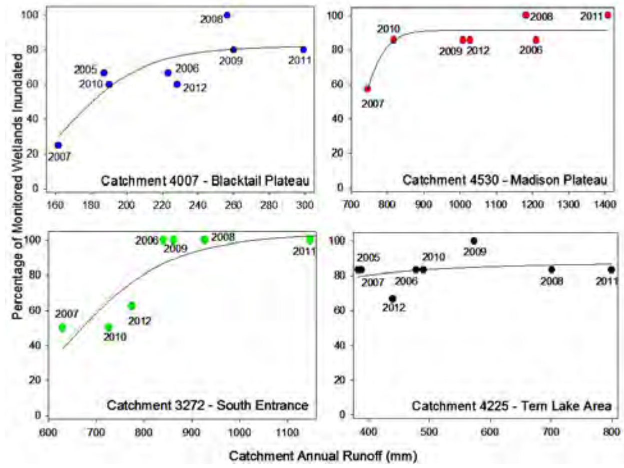


Figure 4. Percentage of monitored wetlands inundated annually for 4 distinct regions (Blacktail Plateau, Madison Plateau, South Entrance, and Tern Lake area) of Yellowstone National Park and the relationship with catchment-level estimates of runoff. Estimates of runoff vary dramatically by location (see individual x-axes for annual variations in runoff). Curves represent best fit curves using a logistic function.

The annual variation in flooding described above is apparent in a series of photos taken of wetland site 3 in catchment 4007 located on the Blacktail Plateau (photo 2). This isolated wetland was dry by early July in 2005, 2006, 2007, and 2010. Although the wetland was inundated in other years (2008, 2009, 2011, and 2012), the amount of water varied. When this site is inundated, western tiger salamanders and boreal chorus frogs breeding was documented. Even though wetlands in southern Yellowstone are expected to be less tied to annual weather patterns because of greater runoff, they exhibited similar drying during years with low precipitation and warm temperatures (see site 2-3272 in photo 3).

Chorus frog occurrences in monitored catchments were strongly related to annual runoff (figure 5). The lowest number of documented occurrences of chorus frog breeding was in 2007, the driest year within our monitoring record and a year when > 40% of monitored wetlands were dry. During that year, chorus frog breeding was documented in only 60 wetlands across both parks. In contrast, surveys in 2011, when approximately 96% of all monitored wetlands were inundated, documented chorus frog breeding occurred in 110 wetlands.

Impacts of Climate Change on Wetlands of the GYE

Wetlands within parts of the GYE, specifically Yellowstone's Northern Range, are shrinking or drying as a consequence of recent temperature and precipitation trends (Schook 2012). In the Northern Range, McMenamin et al. (2008) found the number of inundated wetlands declined from the early 1990s to late 2000s. Our data confirmed wetland inundation in the Northern Range and elsewhere in the GYE are vulnerable to annual variations in temperature and precipitation, and long-term trends in climate. Our annual monitoring data suggest chronic repetition of dry, warm years, like in 2007, could lead to a decline in upwards of 40% of the region's wetlands. This decline could ultimately reduce the distribution and abundance of wetland-dependent taxa, including boreal chorus frogs. Chorus frogs may be the most vulnerable of the GYE's amphibian species to climate because they prefer shallow, ephemeral wetland habitats. The negative response described between boreal chorus frog breeding habitat and dry, warm years underestimates the effects of wetland drying on this species. Even if breeding was documented, we have informally observed the drying of some sites after our annual surveys are conducted but prior to completion of amphibian metamorphosis which can cause reproductive failure. The strong relationship between annual runoff, wetland inundation, and chorus frog breeding occurrence foretell rough times for amphibians if projected drought increases occur.

Declines in water-levels and drying of wetlands could affect a number of other species (e.g., moose, beaver, trumpeter swans, and sandhill cranes) dependent on inundated wetlands for survival (Bilyeu et al. 2008, NRC 2002, White et al. 2011). Although the link between wetland loss and biodiversity is somewhat predictable, changes to other ecosystem services (i.e., benefits and experiences humans obtain from wetlands such as groundwater recharge, pollution filtration) have not been carefully considered. Generally, wetland loss is expected to reduce plant productivity, which limits the carbon sequestration potential of landscapes, affect hydrologic flow paths and water storage within floodplains and uplands, alter soundscapes, and affect wildlife viewing opportunities (Pijanowski et al. 2011, Turner and Daily 2008, Zedler 2003). Loss of wetlands due to drying could also remove natural fire breaks important for managing low to moderate intensity wildfires (Swanson 1981).

Wetlands in Yellowstone's Northern Range may be particularly vulnerable to drying because this region has relatively low amounts of precipitation, elevated temperatures, limited runoff, and declining snowpack and ground water levels (McMenamin et al. 2008, Ray et al. 2014, Schook 2012, Wilmers and Getz 2005). Combined, these conditions have already led to wetland drying and shrinking in the last few decades (McMenamin et al. 2008, Schook 2012). The Northern Range has unique characteristics, but may serve as an indicator for other parts of Yellowstone (e.g., Bechler Meadows) and Grand Teton (e.g., Antelope Flats) where high temperatures lead to high evaporative losses and reduced runoff. More troubling, the region as a whole is projected to experience continued warming over the next century (possibly 5.4° F in the next 50 years; Hansen et al. 2014). Given these projections, widespread changes to wetlands are expected.

Our monitoring data indicated in the driest years, approximately 40% of Yellowstone's and Grand Teton's monitored wetlands were dry by June or mid-July (figure 2). In years with reduced precipitation, high temperatures, and limited runoff, wetland drying was widespread but not uniform across the region (figure 4). In some monitored catchments, no change was detected in the number of wetlands present across years. These wetlands may be hydrologically connected to permanent water bodies (e.g., Yellowstone River or Yellowstone Lake) or exist at higher elevations or locations receiving more snow (e.g., high in the Tetons). In contrast, catchments monitored in Yellowstone's Northern Range in 2007 supported only half (≤ 50%) of the wetlands present in wet years (Ray et al. 2014). The inundation response of Northern Range wetlands to annual variations in surface runoff highlights the importance of runoff contributions, but indicates these hydrologically-isolated glacial wetlands (e.g., kettle ponds) are also strongly influenced by regional groundwater levels and long-term climate conditions (McMenamin et al. 2008). Documenting relationships between air temperature, precipitation, runoff, and wetland inundation is a necessary first step to identifying which regions, catchments, and wetlands are most susceptible to drying and, in turn, which taxa and ecosystem services will be lost.

During our monitoring record, calendar years 2005, 2007, and 2010 all represented low runoff years. These years had variable amounts of annual precipitation, but temperatures during these years were higher than the 30-year average (figure 2). We emphasize this latter point because it demonstrates the influence of air temperature on annual runoff estimates and forecasts for this region's continued warming (Pedersen et al. 2011, Hansen et al. 2014). Higher air temperatures contribute directly to soil drying which, in turn, affects how much precipitation infiltrates rather than runs off the landscape. We believe signs of future warming will continue shrinking and drying of wetlands throughout some regions of the GYE. Our annual monitoring is critical to both documenting and predicting how climate will continue to influence wetlands of this region.

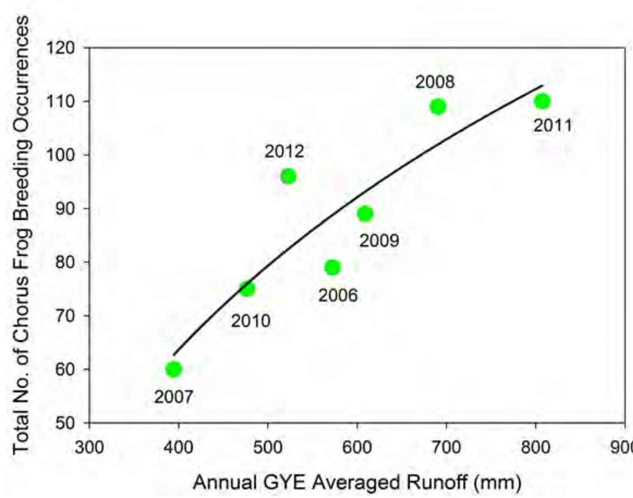


Figure 5. Total number of boreal chorus frog breeding occurrences documented annually in the GYE study area and average annual runoff for the region. Runoff was averaged across all wetlands monitored as part of the long-term monitoring effort. Relationship is statistically significant and explains more than 80% of the documented variation in chorus frog occurrences ($R^2 = 0.82$).

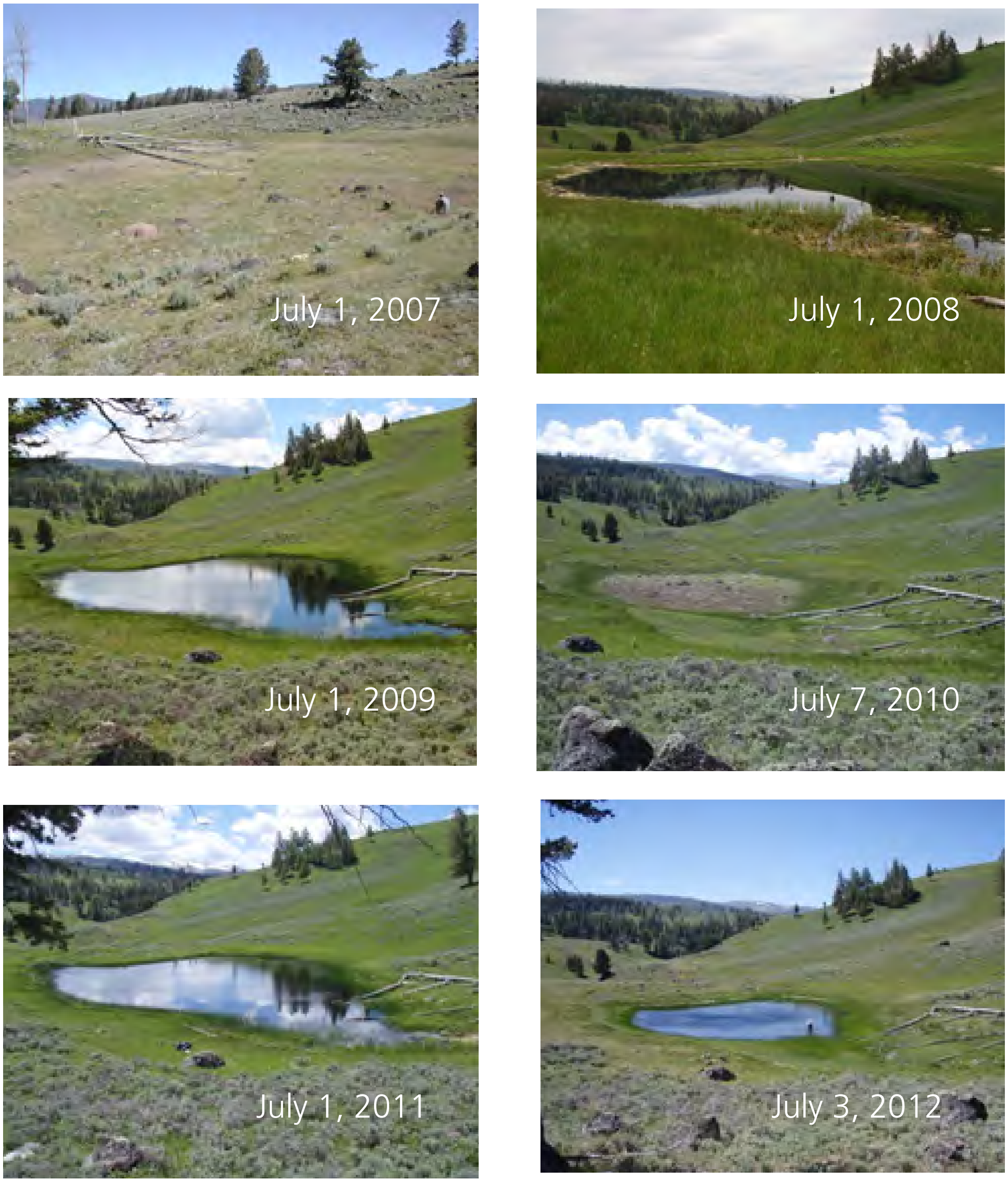


Photo Series 2. Photographic history of site 3 from Yellowstone Catchment 4007 located on the Blacktail Plateau in Yellowstone's Northern Range. Note that the location where the photo was taken changed between 2007 and 2008, but 2007 does depict dry conditions at this site.*

**Although photo dates vary among years, all photos in Photo Series 2 & 3 were taken prior to amphibian metamorphosis when amphibian larvae (e.g., tadpoles) are dependent on standing surface water for survival.*

Photo Series 3. Photographic history of site 2 from Yellowstone Catchment 3272 located near the South Entrance Station.*

The Continued Need for Wetland Monitoring

In Yellowstone and Grand Teton national parks, annual amphibian and wetland habitat monitoring (see Gould et al. 2012) has greatly increased the understanding of wetland vulnerability and links between annual wetland drying and climate. Additionally, monitoring information will inform conservation decisions by providing annual, spatially balanced evidence about the distribution and occurrence of wetlands and amphibians across the GYE. Monitoring data also reduce uncertainty surrounding wetland resources and strengthens opportunities to make informed, science-based decisions that will benefit wetlands and wetland-dependent taxa in a changing climate.

Given our results and the NPS's commitment to wetland protection (Director's Order #77-1) through a goal of 'no net loss of wetlands,' we present four themes to consider. We believe these measures may contribute to the future protection of valuable wetland resources in the Greater Yellowstone Ecosystem:

1. Consider expanding and prioritizing wetland inventories to ensure proper protection, management, and planning around existing wetland resources. Conservation planning would benefit from knowledge of the location, extent, and description of major biological features and ecosystem services of existing wetland resources. This up-to-date information could be combined with temperature, precipitation, and runoff data to identify wetlands most vulnerable to climate change.

2. Identify degraded or disturbed (e.g., through the introduction of nonnative fish) wetlands that could be restored to 'pre-disturbance conditions.' Recent work confirms restoration activities can benefit wetland-dependent taxa, including amphibians, by increasing habitat complexity, re-connecting wetlands, and removing nonnative species (Green et al. 2013, Hossack et al. 2013, Shoo et al. 2011).

3. Recognize the importance of the beaver to sustaining and creating wetlands. Wetlands, amphibians, and other wetland-dependent taxa are strongly linked to the presence of beaver in the Northern Rockies (Bilyeu et al. 2008). Natural and management-related changes in beaver abundance during the 20th century resulted in lower water tables and fewer streamside and floodplain wetlands (Bilyeu et al. 2008, Marshall et al. 2013, Persico and Meyer 2013).

4. Increase public and visitor awareness about the importance of wetlands and vulnerability to climate change. Increased awareness through existing interpretation and education programs (see Wetlands in the National Parks[1] and NPS Response to Climate Change[2] for more information) or through alternative education models. Regardless, the information collected through our on-going monitoring efforts could be used to deliver compelling information about the effects of climate change on wetland resources and engage some of the 3.5+ million people who visit Yellowstone and Grand Teton national parks annually.

[1]Wetlands in the National Parks: http://www.nature.nps.gov/water/wetlands/aboutwetlands.cfm

[2]NPS Response to Climate Change: http://www.nps.gov/subjects/climatechange/response.htm

Literature Cited

Bilyeu, D.M., D.J. Cooper, and N. Thompson Hobbs. 2008. Water tables constrain height recovery of willow on Yellowstone's northern range. Ecological Applications 18(1):80-92.

Copeland, H.E., S.A. Tessman, E.H. Girvetz, L. Roberts, C. Enquist, A. Orabona, S. Patla, and J. Kiesecker. 2010. A geospatial assessment on the distribution, condition, and vulnerability of Wyoming's wetlands. Ecological Indicators 10(4):869-879.

Corn, P.S., M.L. Jennings, and E. Muths. 1997. Survey and assessment of amphibian populations in Rocky Mountain National Park. Northwestern Naturalist 78:34-55.

Corn, P.S. 2003. Amphibian breeding and climate change: the importance of snow in the mountains. Conservation Biology 17(2):622-625.

Dahl, T.E. 1990. Wetland losses in the United States 1780s to 1980s. Department of the Interior, U.S. Fish and Wildlife Service, Washington, D.C.

Drost, C.A., and G.M. Fellers. 1996. Collapse of a regional frog fauna in the Yosemite area of the California Sierra Nevada, USA. Conservation Biology 10(2):414-425.

Elliot, C.R., and M.M. Hektner. 2000. Wetland resources in Yellowstone National Park. Yellowstone National Park, Wyoming.

Fellers, G.M., K.L. Pope, J.E. Stead, M.S. Koo, and H.H. Welsh, Jr. 2008. Turning population trend monitoring into active conservation: Can we save the Cascades frog (*Rana cascadae*) in the Lassen Region of California. Herpetological Conservation and Biology 3(1):28-39.

Gould, W.R., D.A. Patla, R. Daley, P.S. Corn, B.R. Hossack, R. Bennetts, and C.R. Peterson. 2012. Estimating occupancy in large landscapes: Evaluation of amphibian monitoring in the Greater Yellowstone Ecosystem. Wetlands 32(2):379-389.

Green, A.W., M.B. Hooten, E.H. Campbell Grant, and L.L. Bailey. 2013. Evaluating breeding and metamorph occupancy and vernal pool management effects for wood frogs using a hierarchical model. Journal of Applied Ecology 50(5):1116-1123.

Hansen, A.J., N. Piekielek, C. Davis, J. Haas, D.M. Theobald, J.E. Gross, W.B. Monahan, T. Oliff, and S.W. Running. 2014. Exposure of U.S. National Parks to land use and climate change 1900-2100. Ecological Applications. 24(3):484-502.

Hossack, B.R., M.J. Adams, C.A. Pearl, K.W. Wilson, E.L. Bull, K. Lohr, D. Patla, D.S. Pilliod, J.M. Jones, K.K. Wheeler, S.P. McKay, and P.S. Corn. 2013. Roles of patch characteristics, drought frequency, and restoration in long-term trends of a widespread amphibian. Conservation Biology 27(6):1410-1420.

Intergovernmental Panel on Climate Change. 2008. Climate change and water. B.C. Bates, Z.W. Kundzewicz, S. Wu, and J.P. Palutikoff, editors. Technical paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, Switzerland.

Junk, W.J., M. Brown, I.C. Campbell, M. Finlayson, B. Gopal, L. Ramberg, and B.G. Warner. 2006. The comparative biodiversity of seven globally important wetlands: A synthesis. Aquatic Sciences 68(3):400-414.

Koch, E.D., and C.R. Peterson. 1995. Amphibians & reptiles of Yellowstone and Grand Teton national parks. University of Utah Press, Salt Lake City, Utah.

Marshall, K.N., N. Thompson Hobbs, and D.J. Cooper. 2013. Stream hydrology limits recovery of riparian ecosystems after wolf reintroduction. Proceedings of the Royal Society B: Biological Sciences 280(1756):20122977.

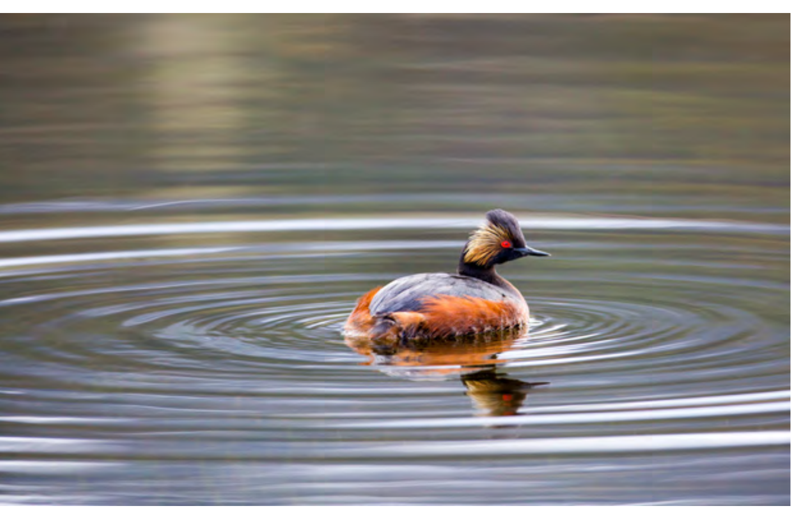
McMenamin, S.K., E.A. Hadly, and C.K. Wright. 2008. Climatic change and wetland desiccation cause amphibian decline in Yellowstone National Park. PNAS 105(44):16988-16993.

Mitsch, W.J., and J.G. Gosselink. 2007. Wetlands, 4th edition. John Wiley & Sons, Inc. Hoboken, New Jersey.

Nicholoff, S.H. 2003. Wyoming bird conservation plan. Version 2.0. Wyoming Partners in Flight. Wyoming Game and Fish Department, Lander, Wyoming.

National Research Council. 2002. Ecological dynamics of Yellowstone's Northern Range. National Academy Press, Washington, D.C.

Pedersen, G.T., S.T. Gray, C.A. Woodhouse, J.L. Betancourt, D.B. Fagre, J.S. Littell, E. Watson, B.H. Luckman, and L.J. Graumlich. 2011. The unusual nature of recent snowpack declines in the North American Cordillera. Science 333(6040):332-335.



Persico, L., and G. Meyer. 2013. Natural and historical variability in fluvial processes, beaver activity, and climate in the Greater Yellowstone Ecosystem. Earth Surface Processes and Landforms 38(7):728–750.

Pijanowski, B.C., L.J. Villaneuva-Rivera, S.L. Dumyahn, A. Farina, B. L. Krause, B.M. Napoletano, S.H. Gage, and N. Pieretti. 2011. Soundscape ecology: The science of sound in the landscape. BioScience 61(3):203-216.

Prigent, C., E. Matthews, F. Aires, and W.B. Rossow. 2001. Remote sensing of global wetland dynamics with multiple satellite datasets. Geophysical Research Letters 28(24):4631-4634.

Ray, A.M., A.J. Sepulveda, B. Hossack, D. Patla, and K. Legg. 2014. Using monitoring data to map amphibian hotspots and describe wetland vulnerability in Yellowstone and Grand Teton national parks. Park Science 31:112-119.

Schook, D.M. 2012. Climatic and hydrologic processes leading to recent wetland losses in Yellowstone National Park, USA. Thesis, Colorado State University, Fort Collins, Colorado,USA.

Shoo, L.P., D.H. Olson, S.K. McMenamin, K.A. Murray, M. Van Sluys, M.A. Donnelly, D. Stratford, J. Terhivuo, A. Merino-Viteri, S.M. Herbert, P.J. Bishop, P.S. Corn, L. Dovey, R.A. Griffiths, K. Lowe, M. Mahony, H. McCallum, J.D. Shuker, C. Simpkins, L.F. Skerratt, S.E. Williams, and J.M. Hero. 2011. Engineering a future for amphibians under climate change. Journal of Applied Ecology 48(2):487-492.

Swanson, F.J. 1981. Fire and geomorphic processes. Pages 401– 420 in H.A. Mooney, T.M. Bonnicksen, N.L. Christensen, J.E. Lotan, and W.A. Reiners, editors. Proceedings of Conference on Fire Regimes and Ecosystems, 11-15 December 1979, Honolulu, HI. General Technical Report WO-26. U.S. Department of Agriculture Forest Service, Washington, DC.

Turner, R.K., and G.C. Daily. 2008. The ecosystem services framework and natural capital conservation. Environmental and Resource Economics 39(1):25-35.

Wake, D.B., and V.T. Vredenburg. 2008. Are we in the midst of the sixth mass extinction? A view from the world of amphibians. PNAS 105:11466-11473.

White, P.J., K.M. Proffitt, T.P. McEneaney, R.A. Garrott, and D.W. Smith. 2011. Yellowstone's trumpeter swans in peril? Yellowstone Science 19(3):12-16.

Williams, D.D. 1997. Temporary ponds and their invertebrate communities. Aquatic Conservation: Marine and Freshwater Ecosystems 7(2):105-117.

Wilmers, C.C., and W.M. Getz. 2005. Gray wolves as climate change buffers in Yellowstone. PLoS Biology 3(4):e92.

Zedler, J.B. 2003. Wetlands at your service: Reducing impacts of agriculture at the watershed scale. Frontiers in Ecology and the Environment 1(2):65-72.

Zedler, J.B., and S. Kercher. 2005. Wetland resources: Status, trends, ecosystem services, and restorability. Annual Review of Environmental Resources 30:39-74.

YS

Andrew Ray (pictured below) is an Aquatic Ecologist with the National Park Service's Greater Yellowstone Network. Andrew has a PhD from Idaho State University, MS from Northern Michigan University, and BS from Purdue University. He works on wetland and amphibian monitoring efforts in Yellowstone and Grand Teton national parks and water quality studies in Bighorn Canyon National Recreation Area, Grand Teton NP, and Yellowstone NP.

Photo by: Kristen Inbody, Great Falls Tribune

Adam Sepulveda is a research zoologist with the U.S. Geological Survey's Northern Rocky Mountain Science Center. His research focuses on native amphibians, aquatic invasive species, and wetland dynamics.

Blake Hossack works for the U.S. Geological Survey Northern Rocky Mountain Science Center. He is stationed at the Aldo Leopold Wilderness Research Institute in Missoula, MT. With various state and federal partners, he coordinates long-term amphibian research in the Greater Yellowstone Ecosystem, Glacier National Park, and the Desert Southwest. He holds a BS in Wildlife Biology from the University of Montana, MS in Wildlife Resources from the University of Idaho, and a PhD in Fish & Wildlife Biology from the University of Montana.

Debra Patla has served as field coordinator of the amphibian monitoring program in Yellowstone and Grand Teton national parks since 2000. Her work with amphibians in Yellowstone began in 1993, with her MS research (Idaho State University) investigating the decline of a Columbia spotted frog population. She is a Research Associate of the Northern Rockies Conservation Cooperative.

David Thoma, see page 27.

Robert Al-Chokhachy is a Research Fisheries Biologist with the U.S. Geological Survey's Northern Rocky Mountain Science Center in Bozeman, MT, who conducts applied analytical and field research to help inform strategies for conservation.

Andrea Litt is an assistant 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 to develop tools for restoration, and designing monitoring programs. She has a BS in zoology from the University of Wisconsin, a MS in wildlife ecology and conservation from the University of Florida, and a PhD in wildlife science with a minor in statistics from the University of Arizona.

CLIMATE CHANGE & THE NPS

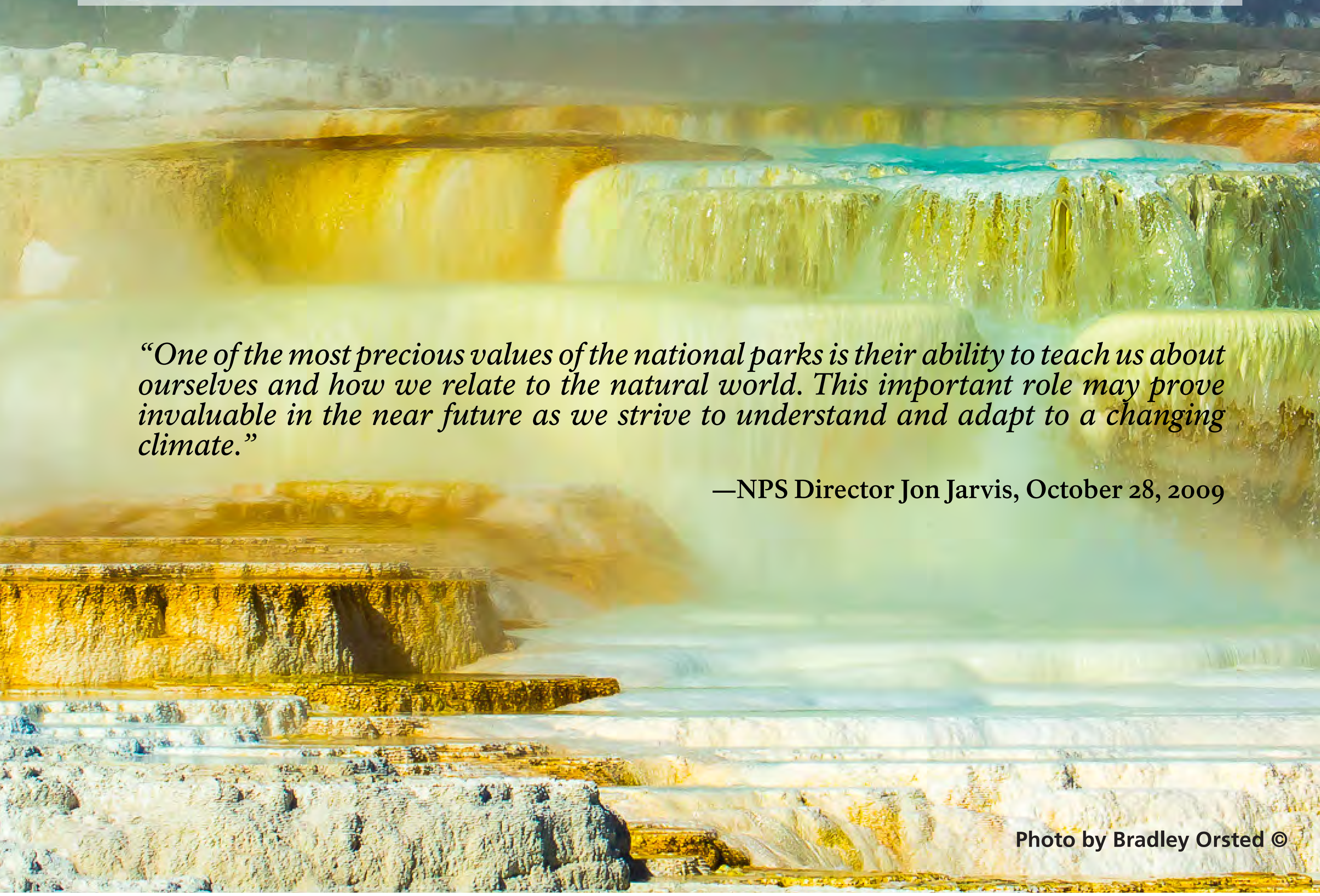
Discover how climate change is affecting our nation's treasures, what the National Park Service is doing about it, and how you can help.

www.nps.gov/subjects/climatechange/climatequestions.htm

Despite the preponderance of scientific evidence about the realities of climate change, in some cases the media still portrays it as a controversy. This leads to confusion and many people are left with questions about climate change. Explore some of the frequently asked questions about climate and climate change.

www.nps.gov/subjects/climatechange/response.htm

Responding to climate change is the greatest challenge facing the National Park Service today. Our national parks contain the most treasured landscapes and important historical sites in this country. They are also the most vulnerable. National parks have always helped us better understand the workings of our planet, the lessons of history, and our relationship to the world around us. Even under the threat of climate change, these natural and cultural resources can teach us how our planet is changing and show us a way to continue to preserve them for future generations.



"One of the most precious values of the national parks is their ability to teach us about ourselves and how we relate to the natural world. This important role may prove invaluable in the near future as we strive to understand and adapt to a changing climate."

—NPS Director Jon Jarvis, October 28, 2009

Photo by Bradley Orsted ©

Birds of the Molly Islands: The "Boom & Bust" Nesting Cycle Turns "Bust Only"

YPF

Lisa Baril

Adult American white pelicans floating on the Molly Islands after the breeding season.

Rocky and Sandy islands, measuring just over a combined acre, barely emerge above the water in the southern end of Yellowstone Lake's southeastern arm; yet these two islands, collectively known as "the Molly Islands," support four species of colonial nesting waterbirds. Hundreds of American white pelicans (*Pelecanus erythrorhynchos*), double-crested cormorants (*Phalacrocorax auritus*), California gulls (*Larus californicus*), and Caspian terns (*Hydroprogne caspia*) compete for prime nesting locations during Yellowstone's brief summer.

Historically, reproduction for these species has been boom and bust (Diem and Pugesek 1994). In some years nesting success is extremely high with hundreds of young produced, while in other years only a handful or none have fledged. These long-lived birds are adapted to cope with boom and bust cycles, but more recently the boom and bust cycle is becoming bust only. The number of pelicans, cormorants, and gulls fledged from the Molly Islands has declined since the early 1990s; and Caspian terns haven't nested there since 2005. The reasons are not well understood, but a previous study indicates certain environmental factors are associated with low reproduction for pelicans nesting there (Diem and Pugesek 1994).

The Molly Islands have supported colonial nesting waterbirds since at least 1890; and while some data exist for this early period, they are difficult to interpret because of human disturbance and heavy-handed management during the first half of the 20th century (Pritchard 1999). But by the mid-1960s human disturbance was virtually eliminated, allowing biologists to study the Molly Islands under natural conditions.

The Molly Islands on June 22, 2011, just before they were flooded by spring snowmelt after one of the highest snow years on record.

During 1966-1987, biologists surveying nesting pelicans by canoe found annual variation in lake water levels partially explained their boom and bust nesting cycle (Diem and Pugesek 1994). When the lake reached 1.4 m above the low water mark, as measured by the Bridge Bay water gauge, the majority of nests flooded; but it took more than one day of high water to produce a "busted" reproductive season. Reproduction was especially low when lake levels exceeded 1.4 m for 29 days or more. Extended periods of high water not only flood existing nests, but prevent pelicans from re-nesting. High lake levels also reduce foraging success. Pelicans forage cooperatively in shallow water, the availability of which is diminished during high water years.

Late ice-out dates were also associated with fewer fledged pelicans. The breeding season for pelicans begins as soon as the ice comes off the lake and lasts about 15 weeks. The longer the ice persists, the shorter the nesting season. And similar to high water levels, the duration of ice cover influenced foraging success since pelicans must expand their foraging range to find adequate food sources in late ice-out years.

I examined lake water levels and ice-out dates to determine their role, if any, in current declines for all four species of colonial nesting waterbirds during 1990-2013. I found a significant negative correlation between the number of days where the water level exceeded 1.4 m and the number of young pelicans produced. Although the number of young gulls also declined along with an increase in the number of high water days, the relationship was weak. There was no relationship between water level and reproduction for cormorants and terns.

Cormorants tend to nest on the highest part of the islands making them less susceptible to fluctuations in water levels, even when water levels rise by as much as 2 m; however, during extremely high water years (e.g., 2011) the islands may be completely flooded. Annual reproduction may also be less susceptible to this variable because, unlike surface-foraging pelicans, cormorants can dive up to 45 m for fish. Terns nest on the lowest part of the islands so their nests are expected to flood first, which if present they do. However, none have nested there since 2005, so other factors may be responsible for their declines.

The number of pelicans fledged from the Molly Islands was negatively correlated with ice-out dates; but there was no relationship between ice-out date and the number of gulls, terns, or cormorants fledged. This may be related with timing of arrival. Pelicans arrive on the Molly Islands and begin nesting before the other species. Although all four species have about the same incubation period (27-33 days), pelicans and gulls have the longest nestling stage (between 9-10 weeks), whereas terns fledge in five weeks and cormorants fledge in six or seven weeks.

At least at this scale, ice-out date and lake water levels do not appear to play a strong role in cormorant, gull, or tern reproduction; but as found in the earlier study, these variables are important to pelican reproduction. Lake water levels and ice-out date are determined by snowpack, spring air temperatures, and the magnitude and timing of spring precipitation; but how these factors interact and vary under climate change is not well understood and difficult to predict. Wetland areas are predicted to decline and some kettle ponds and small lakes are already drying up (Schook and Cooper 2014). Species like trumpeter swans (*Cygnus buccinator*) and common loons (*Gavia immer*) nesting in these areas may already be experiencing the effects of reduced nesting habitat.

The importance of these weather variables to colonial nesting waterbirds may be masked by declines in Yellowstone cutthroat trout (*Oncorhynchus clarki bouvieri*) since the introduction of lake trout (*Salvelinus namaycush*) to Yellowstone Lake during the 1980s. Cutthroat trout are the main food source for pelicans, cormorants, terns, and, to a lesser extent, gulls. Furthermore, an increase in the number of bald eagles at Yellowstone Lake has probably compounded the effects of fewer Yellowstone cutthroat trout there (Baril et al. 2013). During the 1960s-1980s, bald eagles consumed about 30% fish (Swenson et al. 1986), but may be shifting to a bird-based diet in the absence of cutthroat trout (Baril et al. 2013).

Climate change is only as important as its impact on ecosystem processes; but understanding how shifts in climate is affecting, or has affected, park resources requires comparable long-term data. Some of the best examples of how climate change has impacted wildlife and ecosystem processes comes from the ornithological literature, primarily because of birds' rapid response to climatological shifts (Crick 2004). Expanding on current ornithological research within Yellowstone may further our understanding of climate change effects on park resources and should be considered as a priority for future studies.

Audubon Birds & Climate Change Report

Last summer Audubon released a report on how climate change will likely impact the ranges of North America's 588 bird species. Scientists used more than 30 years of Christmas Bird Count and Breeding Bird Survey data to map where each species' ideal climate envelope is likely to be by 2080 given current climate change scenarios. They found that 314–more than half of all North American bird species–are climate endangered or threatened. These are species expected to experience a 50% or more range loss by 2080. The most climate endangered birds will experience this loss by 2050. Disturbingly, more than half of Yellowstone's 156 breeding birds are on that list, and a further 31 species on the list either winter in Yellowstone or pass through during migration. And it's not just species we might expect to be affected by climate change like common loons, trumpeter swans, and black-rosy finches. The list includes common species, such as black-billed magpies, common ravens, and even mallards. Even if these species push north into more suitable climate, many may find themselves stranded in unsuitable habitat. For example, sagebrush specialists like the sage thrasher and vesper sparrow will be unable to survive in the boreal forests of Canada. The study highlights the complexity of predicting how species will respond to climate change. The Audubon Birds and Climate Change Report can be found at:

http://climate.audubon.org/

Literature Cited

Baril, L.M., D.W. Smith, T. Drummer, and T. Koel. 2013. Implications of cutthroat trout declines for breeding ospreys and bald eagles at Yellowstone Lake. Journal of Raptor Research 47(3):234-245.

Crick, H.Q.P. 2004. The impact of climate change on birds. Ibis 146:48-56.

Diem, K.L., and B.H. Pugesek. 1994. American white pelicans at the Molly Islands, in Yellowstone National Park: Twenty-two years of boom-and-bust breeding, 1966-87. Colonial Waterbirds 17(2):130-145.

Pritchard, J.A. 1999. Preserving Yellowstone's natural conditions: Science and the perception of nature. University of Nebraska Press, Lincoln, NE, USA.

Schook, D.M., and D.J. Cooper. 2014. Climatic and hydrologic processes leading to recent wetland losses in Yellowstone National Park, USA. Journal of Hydrology 510:340-352.

Swenson, J.E., K.L. Alt, and R.L. Eng. 1986. Ecology of bald eagles in the Greater Yellowstone Ecosystem. Wildlife Monographs 95:3-46.

YS

Lisa Baril has worked as a wildlife biologist for 15 years. In 2009, Lisa earned a master's degree in Ecology from Montana State University, where she explored willow-songbird relationships in Yellowstone's northern range. She joined Yellowstone's Bird Program in 2008 and in 2011 transitioned to the newly developed Yellowstone Raptor Initiative where she is fortunate enough to research golden eagles, red-tailed hawks, peregrine falcons, and other birds of prey. Occasionally, she gets sidetracked with wading birds and songbirds or, as some like to call them, raptor food.

The Rolling Stones of Soda Butte Creek

Tracing the Movement of Individual Gravel Particles Yields Insight on Sediment Transport and Channel Change in a Dynamic Gravel-Bed River

Dr. Carl J. Legleiter & Devin Lea

For the rivers of northern Yellowstone, the only constant is change. Visitors to the park's northeastern corner often gaze across the Lamar River and its principal tributary, Soda Butte Creek, in search of wolves or grizzly bears. Many wildlife enthusiasts return year-after-year; and the more astute among them also might notice, between sightings, that significant changes occur in the streams that flow beneath Jasper Ridge and Mount Norris. This portion of Yellowstone is comprised of readily erodible Eocene volcanic rocks, recently uplifted and carved by glaciers that left behind steep valley walls. The combination of weak rock, high relief, and a propensity for large floods makes the rivers draining this landscape highly dynamic (Meyer 2001), with many reaches experiencing dramatic changes on nearly an annual basis. This perpetual reworking of channel beds, floodplains, and adjacent riparian communities creates an intricate mosaic of terrestrial and aquatic habitats. In this environment, geomorphic complexity fosters biological diversity and provides crucial refugia for some of the park's most important species, including native cutthroat trout. It's also a great spot to watch some rocks roll.

Rivers, Rocks, & Landscapes

Fluvial geomorphology, the scientific discipline concerned with rivers and related landforms, is based upon a fundamental premise: a close coupling exists between the processes of flow and sediment transport that act to shape channels and the size, shape, and spatial arrangement of morphologic elements such as bars, pools, riffles, and bends. In turn, these features exert a direct influence on the processes responsible for their formation and maintenance. In other words, alluvial rivers (those with beds and banks of mobile sediment) are self-formed, the authors of their own geometry. Complex interactions between form and behavior thus dictate how, and how rapidly, a channel's morphology will evolve over time. This evolution might occur in a gradual, relatively predictable manner, as observed along a gently meandering stream like Slough Creek (another tributary to the Lamar), or in more stochastic fits and spurts, as observed along Soda Butte Creek (Legleiter 2014).

This intimate connection between the movement of sediment and the form of a channel also serves as the foundation for an increasingly popular, inverse method of estimating sediment transport rates. The so-called morphologic approach involves inferring patterns and rates of bed material transfer and storage from observations of channel change, which can be obtained via repeat topographic surveys and/or remote sensing. An important advantage of this technique–as opposed to directly measuring moving bedload–is morphologic methods yield an integrated summary of the geomorphic consequences of the transport process (Ashmore and Church 1998). Although volumes of erosion and deposition can be determined by differencing digital elevation models from two distinct "before and after" time periods, determining transport rates requires additional information on the speed at which this sediment is routed through the fluvial system. Such data can be obtained by tracking the movement of individual sediment particles. These "tracer studies" provide a means of assessing the mobility of various grain sizes, determining travel distances, and identifying preferred locations for sediment to come to rest.

Bars form where many individual sediment grains accumulate in a single location, a preferred rest stop for particles to pause and congregate before continuing on. The hypothesis, tested by Pyrce and Ashmore (2003, 2005) in the controlled setting of a laboratory flume, is that bar spacing is roughly equivalent to the distance traveled by most gravel particles during large, channel-forming flows. Some rocks will move farther, some not so far, and others not at all (particularly during dry years); but the majority will travel about 5-7 times the channel width, which also happens to be the average distance between point bars in a meandering stream.

Although Pyrce and Ashmore (2003, 2005) examined path length distributions in a flume, the relationship between travel distance and channel morphology is not as well-established in natural rivers. We highlight results from a long-term tracer study that involved recording a few rolling stones as they made their way down Soda Butte Creek between 2006 and 2011. More specifically, our work was motivated by the following research question: How far along the river do individual sediment grains tend to travel each year, and does this distance reflect the spatial structure of the channel's morphology (i.e., the spacing between bars)? We also compared particle path lengths from three stream reaches with different morphologies and geomorphic histories, and investigated how these distributions were influenced by hydrologic conditions, as indexed by peak flow magnitude during spring snowmelt.

Morphodynamics of Northern Yellowstone's Gravel-bed Rivers

We initiated tracer studies on three reaches of Soda Butte Creek in the summer of 2006: Footbridge, Round Prairie, and Hollywood (figure 1). We randomly sampled gravel particles from the streambed along a series of transects and hauled the rocks back to our field station for tracer installation. Briefly, this process involved: 1) measuring the size and density of each particle; 2) excavating a cylindrical hole in the rock with a hammer drill (figure 2a); and 3) inserting a passive integrated transponder (PIT) tag (figure 2b) and resealing with epoxy.

PIT tags are a type of radio frequency identification technology widely used to track wildlife, including fish, and more recently to trace sediment movement (e.g., Lamarre et al. 2005, Liébault et al. 2012). The pill-shaped tags are passive in that they do not contain a battery but rather are activated when exposed to an electromagnetic field emitted by an antenna. Each tag broadcasts a unique code read by a mobile antenna (figure 2c), allowing individual particles to be identified and relocated without having to excavate the tracer grain from the bed. The most important advantage of PIT tags is that by recording where individual tracers were initially placed and subsequently found, one can learn about bed mobility, particle movement, and depositional setting.

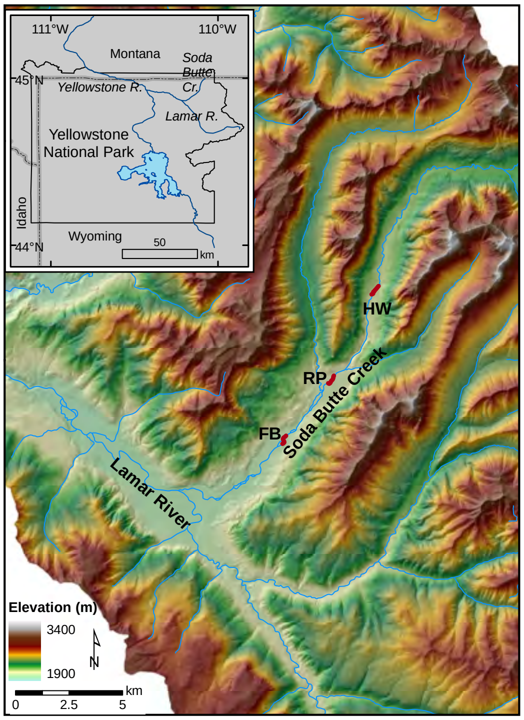


Figure 1. Location map of tracer study performed along three distinct reaches of Soda Butte Creek in the park's northeastern corner. These sites include: Hollywood (HW), Round Prairie (RP), and Footbridge (FB). Adapted from Legleiter (2014).

In this study, the tagged particles were returned to the same cross-sections from which they were obtained and their locations recorded with a GPS. The tracers were carefully inserted into the bed in as natural an arrangement as possible, by replacing a similarly sized particle with one of the tagged gravels. Tracer installation was completed in August and September along with detailed surveys of each study reach. These topographic data defined the morphologic context of the initial tracer locations and also provided digital elevation models for calculating erosion and deposition after the sites were resurveyed (Legleiter 2014).

Tracer recovery involved sweeping channels and bars with a hoop-shaped mobile antenna, performed by the most patient member of our research team (the lead author's father) in a systematic, cross-section-based pattern to avoid gaps in coverage. The search area extended several channel widths beyond where tracers were seeded and increased in size each year as the tracers made their way downstream. When a PIT tag entered the antenna's field of view, we were notified by an audible siren. A handheld computer attached to the antenna displayed the

Figure 2a.

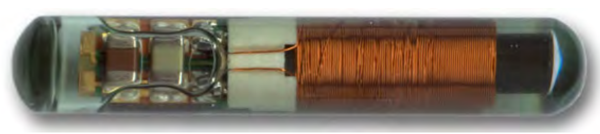


Figure 2b.

Figure 2c.

Figure 2. The tracer study involved (a) using a hammer drill to excavate a hole in each particle, (b) inserting a Passive Integrated Transponder (PIT) tag with a unique radio frequency identification code, and (c) searching for the tagged particles with a mobile antenna.

tag's code, which we recorded along with the GPS coordinates of the tracer's new location. The shortest distance between two points is a straight line; but rivers are curved, so travel distances were measured along the channel centerline using the algorithm developed by Legleiter and Kyriakidis (2006).

Tracer recoveries were limited to 2007 and 2008 for the Round Prairie and Hollywood sites but continued annually through 2011 for the Footbridge Reach. Each year we revisited the last known location of each tracer to determine whether or not the particle had moved, even if we were not able to recover the particle in a new location. By recording the life histories of these rolling stones, we were able to analyze their mobility, travel paths, and depositional fate.

Where Rocks Roll

One challenge of field-based river research, and a reason why flumes provide an appealing alternative, is that the observations one makes depends on a number of variables over which one has no control. Foremost among these factors is the weather, specifically the magnitude of each year's spring flood. Hydrologic conditions for 2006-2011 are summarized in figure 3, which plots streamflow as a function of time for two USGS gaging stations. The gage on Soda Butte Creek located near our Footbridge site was discontinued at the end of the 2008 water year, so we also included data from a gage on the Lamar River farther downstream near Tower. Figure 3b provides an indication of regional hydrologic conditions during the final three years of our study, after the Soda Butte gage was deactivated. In snowmelt-dominated watersheds, sediment movement occurs mainly during spring runoff, with the transport rate depending strongly on the magnitude and duration of high flows. As context for the streamflows observed during our study, the dashed horizontal lines in figure 3 represent the median of the annual peak discharges recorded over the entire period of record for each gage. The median annual flood serves as an estimate of the kinds of large, but not unusual, flows that occur frequently enough to shape a channel. Although varying hydrologic conditions were a complicating factor, this variability created an opportunity to compare particle mobility, path length distributions, and depositional settings between very dry (2007), typical (2008), and relatively high (2010) runoff years.

In essence, the goal of a sediment tracer study is to monitor the movement of individual particles by recording their location each time they are recovered. A sequence of maps depicting the spatial distribution of tracers during each year provides a convenient visual display of how the marked grains traveled downstream and where they paused en route. Tracer maps for the Footbridge site are presented in figure 4 to illustrate this technique. To provide morphologic context for tracer loca-

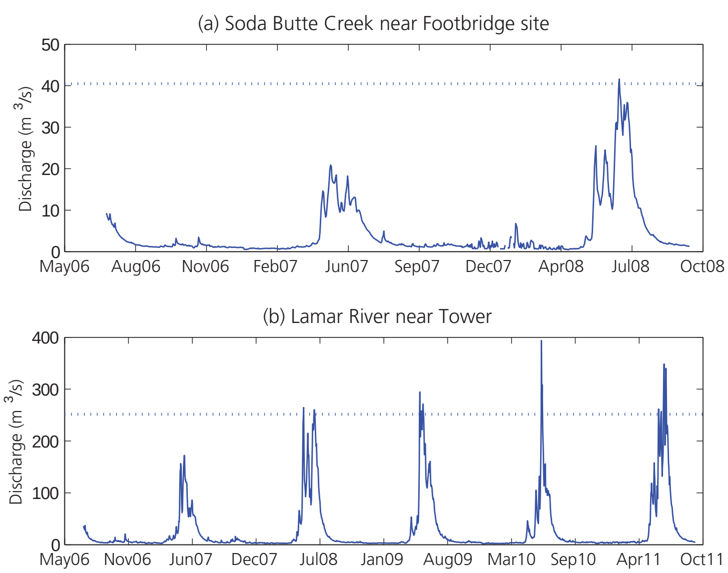


Figure 3. Hydrographs summarizing streamflows during the tracer study for (a) a gage located on Soda Butte Creek near our Footbridge site that was deactivated in 2008 and (b) a gage farther downstream along the Lamar River that is not directly comparable to the Soda Butte site but provides an index of regional hydrologic conditions during the latter portion of the study. The dashed horizontal lines represent the median annual peak discharge for each gaging station over the entire period of record.

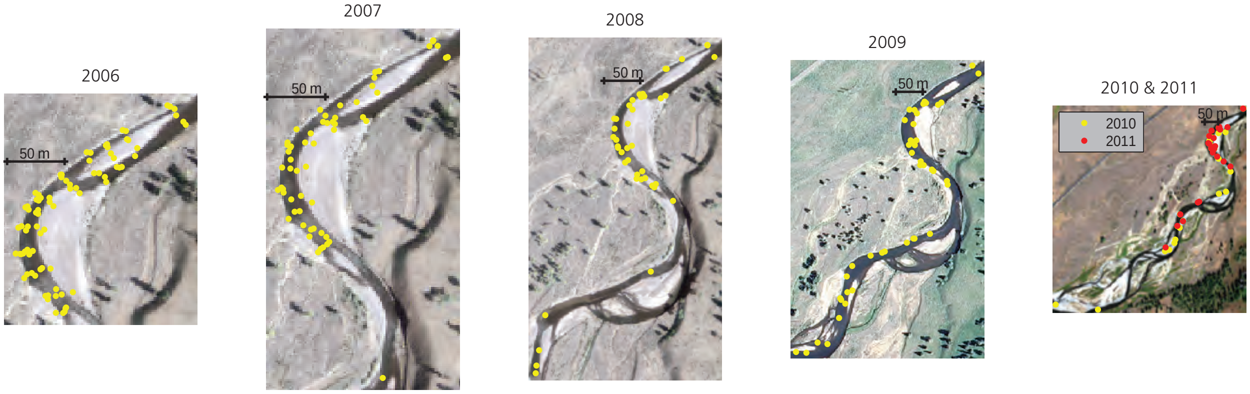


Figure 4. Tracer maps for the Footbridge study site. In the first panel, a 2006 image is used as a backdrop to display the initial placement of the tracers. The second and third panels use the same image as a backdrop but depict the locations of recovered tracers in 2007 and 2008. The fourth panel uses a 2009 image to provide morphologic context for the locations of tracers recovered in 2009. The final panel uses an image from 2011 to show tracer recovery locations for 2010 and 2011. The scale bar represents the same distance in all five maps and is anchored in the same location to provide a consistent spatial reference as we zoom out from the 2006 to the 2009 image and then again to the 2011 image to reflect the dispersion of tracers over a greater distance along Soda Butte Creek.

tions and summarize channel changes that occurred, we used a time series of images as background for these maps. As the tracers traveled farther downstream and dispersed over time, displaying all of their locations required larger image extents; so we zoomed out from one map to the next while retaining a common scale bar anchored in the same location to serve as a consistent reference throughout the time series.

For both the Hollywood and Round Prairie study sites, the infilling of channels that had been active when we initially placed our tracers buried many of them. As a result, we discontinued recovery efforts at these two sites after the 2008 field season. At the Footbridge reach, channel changes were more gradual and the search carried on for three more years through 2011 (figure 4). The first panel of figure 4 shows the initial placement of 83 tracers on a series of cross-sections distributed along the sweeping meander bend to the left (looking downstream, flow is from top to bottom of the image). Using the same 2006 image as a backdrop, the 2007 map shows some of the tracers strayed slightly from the original transects but many remained in place. The most salient feature of this map, and the sole reason for the different scale and extent than the 2006 map, is the single tracer recovered 142 m from its starting point, a full meander wavelength downstream where the channel begins to curve back to the right. This surprising stone indicated that even during low flows when most rocks move little, if at all, the occasional outlier can still sprint several channel widths downstream. Consistent with our observations from the other two sites, this particle came to rest on the lower margin of a point bar, implying gradual downstream translation of the bar.

By 2008, after a more typical spring flood, only 35 of the original 83 tracers were relocated at the Footbridge site; and 11 of those remained in the same locations as in 2007. For the 24 particles that were mobilized, preferred depositional environments included the upstream shoulder of the large point bar on the left bank of the bend in the upper half of the 2008 map, the small but growing bar on the right bank where the channel curves left in the middle of the map, and in shallow water toward the bottom of the image. In 2009, recovered tracers were distributed fairly evenly over an expanded length of Soda Butte Creek, with a dozen particles having traveled a full meander wavelength down the river. Sites of focused deposition were less evident in the 2009 map, perhaps due to the larger runoff during that year, which not only would have entrained more grains but allowed them to remain in motion through areas where they might have been deposited had the discharge been lower. A longer duration of higher flow also might have enabled some tracers to take more than one “hop” during the runoff.

The largest streamflows occurred in 2010 and corresponded to the greatest path lengths we observed at the Footbridge site, including a record leap of 779 m! This grain finally came to rest on a large bar on the right side of the channel, a full three meander wavelengths downstream from its initial 2006 location. The most popular rest stop in 2010 was near the water’s edge on a point bar on the left side of the channel, shown in the middle of the final map in figure 4. This map also includes tracer locations for 2011, when recovery dropped to 18 particles. By this time, we were able to relocate many of the tracers that remained near their previous locations, to which we could navigate using GPS; but the particles that had moved the greatest distances could no longer be found. As time went on and some tracers traveled farther downstream while others remained in place, we were forced to expand our search over a larger area. The increased time and effort required to search this growing domain, coupled with diminishing returns in terms of number of tracers recovered, caused us to end the study after 2011. Even if we're no longer looking for them, the rocks are still out there, rolling along.

A Summary of Particle Path Lengths

Table 1 summarizes tracer recovery, mobility, and travel distances for each reach. Although our recovery efforts provided detailed information on the specific trajectories of each individual grain, we required a more concise summary, aggregated over the population of particles, to gain insight as to typical travel distances, differences among reaches, and hydrologic controls on sediment transport. In figure 5, cumulative distribution functions (CDFs) are used to describe annual travel distances. The vertical axes of these plots indicate the proportion of recovered tracers that traveled a distance less than or equal to the distances on the horizontal axis. Represented in this manner, immobile particles occur in the lower left corner, the rocks rolling the farthest plot at the upper right, and the shape of the line in between depends on the distribution of path lengths for the other tracers. A steep segment of the CDF implies many particles had similar path lengths, resulting in a tight, highly peaked distribution. Conversely, the CDF would rise gradually if the particles were distributed more evenly over a broader range of path lengths. In comparing two CDFs, the distribution with a larger number of longer travel distances would plot farther to the right.

Table 1. Summary of tracer recovery, mobility, and travel distances for each reach. The number of tracers initially placed in 2006 is given in parentheses after the reach name.

	Number recovered	Number of mobile tracers	Median travel distance (m)	Maximum travel distance (m)
Hollywood (77)				
2007	61	48	15.4	257.7
2008	17	16	114	481.3
Round Prairie (74)				
2007	65	46	6.1	187.7
2008	48	31	25.8	234.9
Footbridge (83)				
2007	59	43	6	142.3
2008	35	24	19.9	426.9
2009	35	10	307.1	691.7
2010	26	12	27.9	778.6
2011	18	16	123.7	515.8

For Hollywood, the low flows in 2007 resulted in a large number of immobile or barely mobile particles, with over 50% of the tracers moving less than 10 m (figure 5a). Following the greater runoff in 2008, the CDF shifts noticeably to the right, with only one immobile particle recovered and about half of the tracers moving more than 100 m. The pronounced differences between the 2007 and 2008 path length distributions for Hollywood were at least partially due to the extensive channel changes during this time—incision of a new channel and infilling of the old channel, which buried many of the tagged particles beyond the read range of our antenna system. Nevertheless, our observations—greater path lengths in the year with higher runoff and a path length distribution peaking at a distance of seven channel widths, approximately equal to the spacing between bars—were consistent with the hypothesis that the spatial structure of river morphology reflects the distance traveled by individual sediment particles during channel-forming flow events.

Results from Round Prairie were similar in many respects (figure 5b). In this reach, which is primarily depositional in nature, nearly 70% of the tracers relocated in 2007 were immobile or moved less than 10 m. As in Hollywood, higher flows in the spring of 2008 transported more of our tracers over greater distances, with fewer immobile particles, suggesting flows of sufficient magnitude are needed to transport sediment over significant distances. The connection to channel form is less clear in Round Prairie due to the braided morphology of this reach; bars are arranged irregularly and tend to be more closely spaced.

The Footbridge reach was the most stable site during our investigation, which allowed us to continue tracer recoveries through 2011. Again, the CDF graph indicates that little sediment movement occurred during 2007 (figure 5c). In 2008, recovery dropped to 35 tracers (24 were mobile); but the particles we relocated tended to move farther, as indicated by the CDF's shift to the right. The path length distribution was also less skewed in 2008 than 2007. In 2009, the same number of tracers was recovered, but only 10 were mobile. Based on this small sample size, the path length distribution appeared far more symmetric with relatively few particles moving short distances. The peak flow recorded in 2009 for the Lamar gage exceeded the median annual flood for this station; and the increased

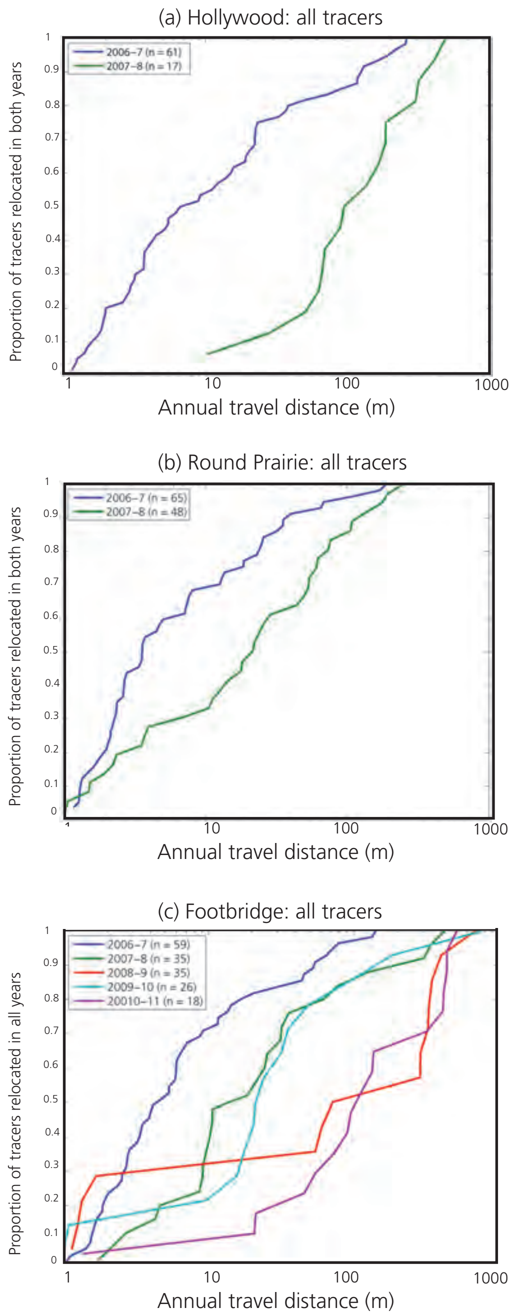


Figure 5. Statistical summary of particle path length distributions during each year for each reach. Annual travel distances for all tracers are represented using Cumulative Distribution Functions (CDF).

magnitude and duration of high flow might have allowed the tracers to take multiple hops during the runoff season. An even higher peak discharge occurred in the spring of 2010 with the greatest single displacement observed at 779 m. Although the peak discharge for 2010 was the largest during our study, the hydrograph in figure 3 indicates the period of high flow was relatively brief, suggesting particles might not have taken as many steps as in the previous year. By 2011, all but 18 of our initial tracers had been lost. Sixteen of the particles recovered in 2011 were mobile and the CDF shifted back to the right. The combination of a larger peak discharge and a longer duration of high flow might have contributed to the greater path lengths in 2011 than 2010. Moreover, the median travel distance for 2011 was roughly equivalent to the spacing between large point bars along this meandering channel. These observations were consistent with the notion that the spatial scaling of river morphology is dictated by the displacement of individual sediment particles from sites of erosion to areas of deposition.

An equilibrium channel morphology, in which a stable form is maintained by an approximate balance between sediment supply and transport capacity, is established over a period of many years. Although the annual travel distances presented in figure 5 and described above provide some sense of the relationship between path length and morphology, a slightly longer-term perspective also is helpful. To gain such a perspective, we calculated the total cumulative travel distance of each tracer over the entire period of study. These cumulative travel distances provided insight on the downstream translation of the tracers and their dispersion over time (figure 6).

Of the three sites, Footbridge was closest to an equilibrium configuration, with only gradual changes occurring from year to year. Cumulative displacements remained small through 2007 and 2008, although higher flows in the latter year expanded the distribution of path lengths. Not until 2009 did the median cumulative displacement increase to three channel widths, with the distribution becoming more symmetric as well. By the end of the study in 2011, the median cumulative travel distance had increased to about five channel widths, implying on average, particles tend to move about one channel width downstream per year. In other words, as in a race, the pack spreads out as time goes on and the stragglers fall farther and farther behind the frontrunners.

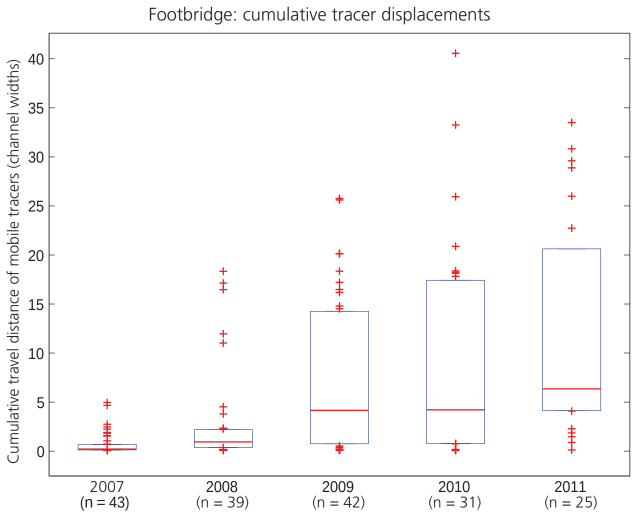


Figure 6. Cumulative travel distances of all recovered tracers for each year in the Footbridge Reach are summarized using a sequence of box plots, in which the red lines indicate the median, the blue boxes encompass the 25th–75th percentiles of each distribution, and the point symbols indicate outliers.

The Rocks Keep on Rolling

Given the limitations of this study (small sample size and low tracer recovery rates), our data support a few tentative conclusions. First, a measure of the central tendency of the distribution of particle path lengths, such as the median travel distance, scales with the point bar spacing typical of meandering channels, provided that streamflows are sufficient to mobilize and transport sediment. Second, path length distributions varied among our three study sites due to their distinct geomorphic characteristics, with greater travel distances occurring in the erosional Hollywood reach than in the depositional Round Prairie site or the relatively stable Footbridge Reach. Third, the displacement of sediment particles, both individually and in aggregate, is influenced by hydrologic conditions, primarily the magnitude and duration of the spring snowmelt, with fewer immobile tracers and greater path lengths during high runoff events. As a final, more qualitative conclusion, this tracer study illustrated the difficulty of river research. Yes, field work can be demanding, but more significant is the intellectual challenge of trying to understand the feedback between form and process that makes gravel-bed streams so dynamic, complex, and aesthetically appealing. Of course, that challenge is why studying rivers is lots of fun, too.

Literature Cited

Ashmore, P.E., and M. Church. 1998. Sediment transport and river morphology: A paradigm for study. Pages 115-148 in P.C. Klingeman, R.L. Beschta, P.D. Komar, and J.B. Bradley editors, Gravel-Bed Rivers in the Environment. Water Resources Publications, Highlands Ranch, Colorado.

Lamarre, H., B. MacVicar, and A.G. Roy. 2005. Using passive integrated transponder (PIT) tags to investigate sediment transport in gravel-bed rivers. Journal of Sedimentary Research 75(4):736-741.

Legleiter, C.J., and P.C. Kyriakidis. 2006. Forward and inverse transformations between Cartesian and channel-fitted coordinate systems for meandering rivers. Mathematical Geology 38(8):927-958.

Legleiter, C.J. 2014. A geostatistical framework for quantifying the reach-scale spatial structure of river morphology: Application to restored and natural channels. Geomorphology 205:85-101.

Liébault, F., H. Bellot, M. Chapuis, S. Klotz, and M. Deschâtres. 2012. Bedload tracing in a high-sediment-load mountain stream. Earth Surface Processes and Landforms 37(4):385-399.

Meyer, G.A. 2001. Recent large-magnitude floods and their impact on valley-floor environments of northeastern Yellowstone. Geomorphology 40(3):271-290.

Pyrce, R.S., and P.E. Ashmore. 2003. Particle path length distributions in meandering gravel-bed streams: Results from physical models. Earth Surface Processes and Landforms 28(9):951-966.

Pyrce, R.S., and P.E. Ashmore. 2005. Bedload path length and point bar development in gravel-bed river models. Sedimentology 52(4):839-857.

YS

Carl Legleiter is an Assistant Professor of Geography at the University of Wyoming. He began working in Yellowstone as an undergraduate at Montana State University, and Soda Butte Creek served as the field area for his dissertation at the University of California Santa Barbara. His research focuses on river morphodynamics and the development of remote sensing techniques for characterizing fluvial systems. Legleiter is shown here with his father Floyd, who played a key role in the tracer study.

Devin Lea earned a BA in Geography from Aquinas College in Michigan and an MA in Geography from UW, where his thesis research focused on connections among channel dynamics, sediment tranport, and the spatial distribution of stream power along Soda Butte Creek.

I AM NOT A SCIENTIST

What is the Difference Between Weather & Climate?

Charissa Reid

As someone who makes her living communicating scientific information to the general public, I often find that I am in possession of more questions than answers. The question I have about climate change is not unfamiliar to scientists in this field: What is the difference between weather and climate? I have heard people in the coffee shop and on the network news make sweeping comments about a week of sunshine or a day of extremely harsh winter weather being an indication of, or an argument against, the very existence of global climate change.

So why is talking about weather different than talking about climate change? I interviewed some of the scientists I know to ask them to help me structure an articulate answer.

Weather is what is happening to us right this moment. It's something that changes quickly and we expect it to change. Weather is a highly dynamic force that compels us to react to our environment on a short term basis. Climate is a long-term trend. It's one of the things that define the part of the planet that we live in and is actually an indication of where we are anchored in relationship to latitude and longitude, to mountain ranges and oceans, and prevailing winds high in the atmosphere.

To use a Yellowstone analogy, weather is the steam from an erupting geyser; climate is the super volcano heating the slowly rising water.

One scientist said, "I have really warm snow boots because I live in the Rocky Mountains. If I move to Florida, I'm going to sell them." Climate dictates the need for the boots; weather gives you a reason to don them before heading out the door.

Climate change is something we know exists. Even on a human scale, events like the Dust Bowl of the 1930s and the Little Ice Age that began in the 1300s are within our collective memory as climate-driven events. We know climate is cyclic in nature although our understanding of why those cycles occur, and how predictable they are, is still relatively unknown.

	1/27/2015 °F	Previous Record of High °F (Year)
Old Faithful	52°	41° (2005)
Mammoth Hot Springs	52°	49° (1942)
Lake Village	42°	40° (1942)

Part of what climate scientists are trying to understand is how human alterations of the atmosphere are related to measurable changes they are documenting in the climate pattern. Yellowstone is an ideal place to study these changes as we have 100 years of reliable weather data on record!

For all of us, scientists and non-scientists alike, the questions are many. Why is a large-scale shift happening in the climate cycle and how are we responsible for this change? What, if anything, can we do about it?

One scientist summed up the concerns that drive his research by saying, "Small changes in climate can have enormous implications for biology, so if we care about our biology, we better start caring about climate. I think it's up to each individual to figure out what way they can contribute to solving the problem instead of creating more of it."

So the next time you hear confusion surrounding the snow outside your door and the questions that climate scientists are grappling with, remember to separate weather and climate in your discussions. It's okay to have questions and, yes, even to be cautious about where this field of study is leading us. Ideally our caution should be fueled by curiosity rather than fear. Because, as I see it, curiosity is what science is all about!

YS

Special thanks to the scientists who helped me answer this question: Dr. Glenn Plumb, Kristin Legg, Dr. David Thoma, & Tom Olliff.

Charissa Reid serves as a graphic designer & writer/editor for the Science Communications Program at the Yellowstone Center for Resources. While not a scientist, her primary interest lies in scientists and what makes them ask the questions they do.

THREE QUESTIONS *for David E. Hallac & Scott Barndt*

Yellowstone Science asked two land managers three questions about their climate change perspectives...

Dave Hallac is the former chief of Yellowstone Center for Resources and is now the superintendent at the Outer Banks Group (NPS).

Scott Barndt is the Ecosystems Staff Officer and a fish biologist for the Custer Gallatin National Forest, United States Forest Service and lives and works in Bozeman, MT.

Yellowstone Science (YS): Do you think that federal agencies should fight climate change by preserving protected areas as they are, or should we adapt to climate change making the best of whatever is to come?

Dave Hallac (DH): I don't think we should fight to keep everything we have today in the face of climate change. I just don't think it's possible. It would be irresponsible for us to not try to reduce carbon emissions and greenhouse gases. That said, individual park service units don't have the capability to change the trajectory of warming on the planet, so because of that, we are most likely unable to reverse climate change in the near term and also most likely unable to feasibly hold back the corresponding ecological impacts that may result when the climate continues to change into the future.

I don't think we should be actively trying to re-engineer Yellowstone National Park by using selectively-bred animals or plants or genetically modified species. I think that would be a very slippery slope in terms of allowing climate change to give us license to totally reengineer our natural areas, and I think the great value of Yellowstone National Park and national parks in general is that they are places where we have generally tried to keep our hands off of the system.

Scott Barndt (SB): Well, at least for us on the national forests, it's really not a black and white choice. The reality is, with the resources we have and the various land designations on national forests the choice is really between choosing to adapt some things in some places; and there are going to be other places where we're going to be sitting back and watching what happens.

For some things in particular, it's probably not a prudent choice. On the Custer Gallatin National Forest, where I work, about half of our landscape is in some sort of protected status, which restricts our management options. There are some things we could do to adapt on those landscapes, but not a lot; and they're also in some pretty inaccessible places, so our options are limited in any case. In those places a lot of the time we're going to be observing what happens with climate change with other factors; but on a lot of other parts of the landscape we will have more opportunities to adapt, and we'll be doing that.

YS: How is climate change information being integrated into land & resource management in your agency?

DH: I think we have become at least aware enough to put more effort into compiling and looking at the trends and patterns of climate that has already been changing, so we've at least brought the information onto our radar screen. I think the Park Service has made it clear that considering the best available science to inform parks on the effects of climate change and seriously rethinking the way that we manage parks and manage our resources is a priority.

A perfect example is whitebark pine. Whitebark pine is a really important native species. It's considered a keystone species in high altitude locations for a variety of reasons, including it's a food value for animals we care about, its role in stabilizing snowpack. It's clearly a really important species some find charismatic as well when

SB: Right now projections for climate change are pretty coarse. It's hard to integrate those into very specific management actions in many cases. We're using the information to filter the choices we make, and we can use it to help prioritize the kinds of things that make sense in the face of climate change no matter where we do them.

If we have some idea about broad landscapes and that some kinds of choices might make more sense in some places than others, part of the challenge for us is having enough site specificity at a scale to help us make finer-scale choices.

We have our forest service climate change adaptation plan, kind of broad-scale direction, with ways to think about it; but then we also have a national roadmap, which includes a climate change scorecard. It is a ten-they're up in the high mountains. That said, whitebark pine is not the defining component of Yellowstone National Park. If we lost whitebark pine, we wouldn't lose Yellowstone National Park.

I put adaptation into two categories. I have a category of what I would call "no regrets, safe to implement," and then the other category of "daring and ecosystem engineering." So the adaptation management options for Yellowstone that I feel comfortable with as division chief are the things that we would have done absent climate change.

Let's presume there are some nonnative species like plants that we have the capability of controlling, have the capability of eradicating, even with climate change. Putting more effort into those things, even if climate change is exacerbating those situations, to me may be a safe-to-implement, no-regret action because that's a nonnative species.

Climate change is not something that's going to happen to us. It's happening. We have a 30-day-longer growing season since 1950. Holy mackerel! I mean it's just mind-boggling. I guess the answer to the question again is–"it depends." If we're talking about a species like the grizzly bear where we went out and caused the decimation of the species and now we're trying to bring them back and it is feasible because they're generalist omnivores–it can be done. So in that case it makes perfect sense to continue measures, but I wouldn't say extraordinary, to preserve those species.

element scorecard; and by the end of fiscal year '15, all national forest and grassland units are supposed to achieve 70 percent, or 7 out of 10 elements on there. Part of it is establishing partnerships both internally and externally. Part of it's getting better information. Part of it is understanding vulnerabilities, and then part of it is actually adaptation planning and implementation. Then, there's one element of the scorecard that's reducing our greenhouse gas impacts.

In the last five years the quality of information has just improved dramatically. When we're building roads and infrastructure with things projected to get hotter and more variability in precipitation, likely more extreme weather events, just making sure that we are really thoughtful about the size of our stream crossings and how close we place facilities to streams are pretty safe ways to adapt to the likelihood that we're going to have more extreme weather and exposing infrastructure and people to that kind of thing.

I think the biggest challenge is really personalizing or making it relevant to the staff day-to-day activities on the job. How do you make it relevant to what someone does on a day-to-day basis?

Natural resource managers, we're used to paying attention to weather and climate overall. It's just that when you're thinking of something that may be as big of a deal as climate change is discussed as being, how do we take that and then make it relevant at the scale at which people do work?

YS: How do you feel your agency can best help their constituency understand climate change?

DH: I actually believe that in every one of these cases when we talk about climate change, I've seen examples of folks that ordinarily might not believe that climate change is occurring; but they can tell you that they've been here for 80 years and there "used to be this much snow at this level of the swing set in their backyard" and now they're likely to see just a little bit of snow on the ground, and they've experienced that in their lifetime and know that things have definitely changed.

Interviews with people that have been around for a long time and hearing non-scientists, not government agencies, talk about changes is actually far more powerful than any scientific data that we can throw out there. It doesn't mean that we don't continue all the science that we're doing, but I think that people's stories are important.

SB: We are getting a little bit better information. I don't think we should be paralyzed as managers waiting for perfect information because that'll never happen. We never have perfect information. We never have all the information we would like to have. We're always making informed choices or balancing the risks–and a lot of times that's a judgment call.

Ultimately, in our jobs, we work for the people of the United States. These lands are to the nation–it's the national park; it's the national forest. So many of these questions come down to what do we value? What's iconic to us? What's meaningful? What do we value more? What do we want to try to hold onto?

We have to engage our folks first, so getting better information and personalizing it for folks is the first step to being able to do something about it.

YS

A Seemingly Small Change in Average Temperature Can Have Big Effects

Dr. Mike Tercek

Worldwide average annual temperatures increased about 1.5°F during 1880–2012 (Hartmann et al. 2013), and scientists predict an additional 3–8°F of warming to occur during the 21st century (Collins et al. 2013). These might seem like small numbers; after all, a busy person might not notice if the temperature in their house changed 8 degrees. A change of 1-3 degrees seems hardly worth talking about, but if you set your thermostat a few degrees lower in winter you'll notice big cost savings over time because you lowered the average temperature.

Averages are one way of describing a set of measurements, but they do not tell the whole story. Figure 1 is an example from Gardiner, Montana, the north entrance to Yellowstone. The graph shows the minimum nighttime temperatures measured during the month of April in two time periods: 1957–1984 and 1985–2012. There are daily April measurements from 28 years in each period, evenly splitting up the 56 years since the weather station starting collecting data.

Here's why a small change in average temperature can have big consequences. The averages of these two time periods are only 3 degrees apart (29 degrees in the early period vs. 32 degrees in the later period), but this relatively small increase in average temperatures has moved the entire bell curve for the later period (red line) to the right. As a result of this shift, there were 98 more frost free April days (days that did not go below freezing) during the later period. This increase, which works out to an extra 3–4 more frost free April days per year, is illustrated by the shaded red area in figure 1. Also notice the tail ends of the bell curve have moved more than the 3 degree shift in averages. Moving the tails made the warmest April nighttime temperature shift by 8 degrees, from 48°F during the

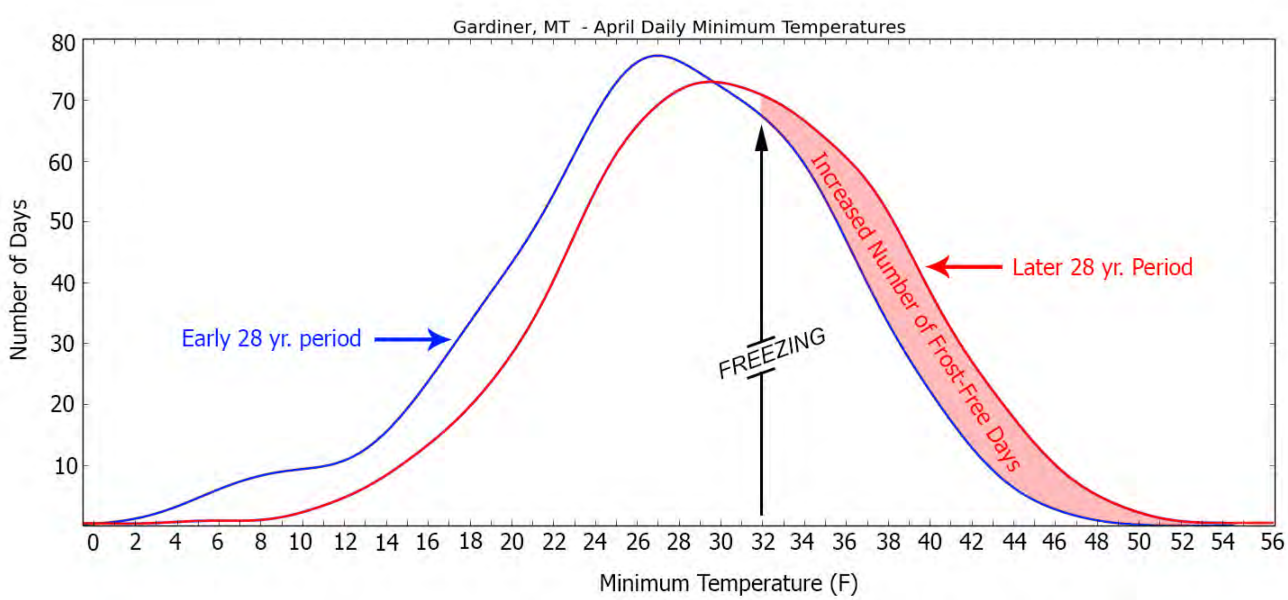


Figure 1. The x-axis is the range of nighttime temperatures measured during all the Aprils in the years 1957 to 2012, and the y-axis is the number of days in which each nighttime temperature was measured.

early period to 56°F during the later period. As a result of this shift, previously rare temperatures, for example 40°F or warmer, occurred more than twice as often (an average of 3.2 vs. 1.4 days per April) in the later period. These patterns are very common throughout the world; as climate changes, the extreme temperatures (maximums and minimums) usually change faster than the averages.

Frost free days signal the start of spring. As you might imagine, the growing season has been getting longer in Gardiner during the last 28 years. The number and timing of freezing days also controls when the snow melts, when streams reach their spring peak flows, and how quickly river levels fall in the dry summer months. A 3 degree average change during April in Gardiner might not seem like much at first; but it has cascading effects on local plants, fish, and wildlife.

Worldwide, average temperature changes can have significant effects. An 8 degree change in your house might not seem like much, but a similar amount of worldwide average warming was responsible for melting ice sheets miles thick and ending the last ice age.

The 5–14°F increase that melted the glaciers during the end of the last glacial period played out over about 8,000 years, and scientists estimate that warming was never more than 1°F per 1,000 years during that time (Masson-Delmotte et al. 2013). In contrast, scientists predict that we will experience 3–8°F of warming in the next 100 years. In other words, the planet will experience about as much warming in the next 100 years as it did in the 8,000 years at the end of the last ice age, but this time it will be 30-80 times faster.

Literature Cited

Collins, M., R. Knutti, J. Arblaster, J.L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver, and M. Wehner. 2013. Long-term Climate Change: Projections, Commitments and Irreversibility. Pages 1029-1136 in T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, editors. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y. Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W. Thorne, M. Wild, and P.M. Zhai. 2013. Observations: Atmosphere and Surface. Pages 159-254 in T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, editors. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Masson-Delmotte, V., M. Schulz, A. Abe-Ouchi, J. Beer, A. Ganopolski, J.F. González Rouco, E. Jansen, K. Lambeck, J. Luterbacher, T. Naish, T. Osborn, B. Otto-Bliesner, T. Quinn, R. Ramesh, M. Rojas, X. Shao, and A. Timmermann. 2013: Information from Paleoclimate Archives. Pages 383-464 in T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, editors. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

YS

Ice Patch Archaeology in the Greater Yellowstone

Dr. Craig M. Lee & Halcyon LaPoint

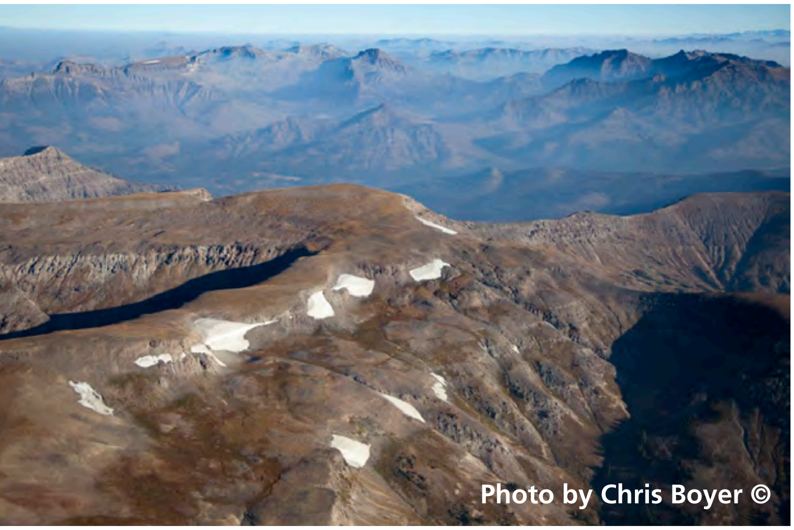


Figure 1. Aerial survey photo of GYE ice patches by Chris Boyer, www.kestrelaerial.com.

Figure 2. Ancient trees revealed by melting ice.

Periglacial alpine snow and ice is melting in the Greater Yellowstone Ecosystem (GYE) and around the world in response to changing weather patterns (figure 1). As it melts, some of this ancient ice is releasing an astonishing array of paleobiological and archaeological material, including trees (figure 2), plants, animals, and insects, as well as rare and unique organic artifacts such as dart shafts (figure 3), basketry, and other pieces of material culture (Lee 2012, Reckin 2013). Consistent with the oral traditions of many tribal groups (KSKC 2014), the GYE ice patch record allows for the conceptualization of the alpine—in ancient times, at least—as an ecosystem in balance where humans and animals alike took advantage of a seasonally-enriched biome. Much remains to be learned, particularly about climate-conditioned human responses in the GYE alpine.

Ice patch resources are finite and may be lost in the next several decades. The exposure of ancient archaeological and paleobiological materials by the retreat of moisture-starved and heat-ravaged ice patches in the GYE is a tangible indication of climate change in the Rocky Mountain West. The impacts transcend the divide between the cultural and natural world. The archaeological record demonstrates repeated use of ice patches by Native Americans for millennia, indicating they were an important element of their sociocultural and geographic landscape.

A recently completed project sponsored by the Greater Yellowstone Coordinating Committee (GYCC) resulted in the identification of over 450 prospective ice patches meeting *a posteriori* criteria developed at known ice patch archaeological and paleobiological sites in the GYE and elsewhere (Andrews et al. 2009, Callanan 2013, Lee et al. 2014). The GYCC provides an ideal supra-level organization for managing the loss of at-risk ice patch resources as a result of climate change. Scientists from the USDA Forest Service, Yellowstone National Park, the Institute of Arctic and Alpine Research at the University of Colorado, the Institute on Ecosystems at Montana State University, and the United States Geological Survey are collaborating to respond and generate relevant environmental and climate proxy data. Conditions permitting, the 2015 field season will provide training opportunities for interested GYE Unit partners as well as the continuation of GYCC-sponsored survey flights to verify potential targets. Importantly, the results of work-to-date were shared with tribal groups in 2014 to solidify partners for future efforts.

Literature Cited

Andrews, T.D., G. MacKay, and L. Andrew. 2009. Hunters of the alpine ice. Blurb Press. http://www.blurb.com/b/1178945-hunters-of-the-alpine-ice.

Callanan, M. 2013. Melting snow patches reveal Neolithic archery. Antiquity 87:728–745.

KSKC. 2014. Ice Patch Archeology in Glacier National Park. YouTube Video published on Jan 30, 2014. https://www.youtube.com/watch?v=w1Vgs9IMixY&feature=youtu.be.

Lee, C.M. 2012. Withering snow and ice in the mid-latitudes: A new archaeological and paleobiological record for the Rocky Mountain region. Arctic 65(Special Issue):165–177.

Lee, C.M., R.L. Kelly, R. Reckin, I.L. Matt, and P.L. Yu. 2014. Ice patch archaeology in western North America. SAA Archaeological Record 14(2):15-19.

Reckin, R. 2013. Ice patch archaeology in global perspective: Archaeological discoveries from alpine ice patches worldwide and their relationship with paleoclimates. Journal of World Prehistory 26:323–385.

YS

Dr. Craig M. Lee is a Research Scientist at the University of Colorado's Institute of Arctic and Alpine Research (INSTAAR) as well as at Montana State University. He is also a Principal Investigator at Metcalf Archeological Consultants, Inc. He researches the archaeoecology of alpine and high latitude environments with an emphasis on sharing the process and results with numerous audiences. He serves on the Boards of Directors for the Lamb Spring Archaeological Preserve, the PaleoCultural Research Group, and the Montana Archaeological Society. He is President of the latter.

Halcyon LaPoint is the Heritage Resources Program Lead for the Custer Gallatin National Forest, Billings, MT. She has worked as a forest archaeologist for over 30 years.

Figure 3. Yellowstone National Park Archaeologist, Dr. Staffan Peterson, with a 3,000-year-old organic mid-shaft from an atlatl dart. Inset is of the conical base of the mid-shaft; two ownership marks are visible on top, midway up the visible portion of the shaft.

Dynamics of Yellowstone's Hydrothermal System

Dr. Shaul Hurwitz & Dr. Jacob B. Lowenstern

Yellowstone's hydrothermal features are spectacular, globally unique, and unexpectedly diverse. Their existence alone led in part to the establishment of Yellowstone as the first national park in the world. The hydrothermal system comprises the largest concentration of geysers and hydrothermal explosion craters on Earth, with more than 10,000 thermal features, including fumaroles, mud pots, frying pans, and varicolored thermal pools. Hot fluids discharged at the surface deposit silica sinter, travertine, native sulfur, and other minerals. The springs host biota from all three domains of life (Bacteria, Archaea, and Eukarya), which use diverse sources of energy for metabolism. Hydrothermal activity is modulated and perturbed by processes that operate over time scales ranging from seconds (e.g., earthquakes), to days (e.g., air pressure and temperature variations), to seasonal (e.g., precipitation, snow melt, lake level), to decadal, centennial, millennial (e.g., caldera inflation and deflation, ice sheet advance and retreat), and even longer (volcanic cycles).

In the recent paper "Dynamics of the Yellowstone Hydrothermal System" published in the journal *Reviews of Geophysics* (Volume 52(3):375-411*), U.S. Geological Survey scientists Shaul Hurwitz and Jacob Lowenstern review the substantial advances that have emerged in the past quarter of a century in understanding the processes operating in Yellowstone's dynamic hydrothermal system. This follows a similar review "Geochemistry and the Dynamics of the Yellowstone Hydrothermal System" published in the journal *Annual Review of Earth and Planetary Sciences* (Volume 17:13-53) written by retired U.S. Geological Survey scientist Robert Fournier in 1989. The collective body of work during the past 25 years documents large changes at many different temporal and spatial scales, and the coupling between physical, chemical, and biological processes.

Hurwitz and Lowenstern demonstrate that the most recent advances stem from the development of modern technologies, densification of monitoring networks, accumulation of large data sets, discovery of hydrothermal vents in Yellowstone Lake, evidence relating thermophile microorganisms to the geochemical cycle, and additional research intensity due to establishment of the Yellowstone Center for Resources in 1993 and the Yellowstone Volcano Observatory in 2001. This progress has built upon more than 140 years of research since the 1870 Washburn expedition, the 1871 Hayden expedition, and the establishment of Yellowstone National Park in 1872.

In addition to reviewing the significant research accomplishments, the recent paper also highlights some unresolved questions and suggests future research directions. Answering the most fundamental question "what does the future hold for Yellowstone?" will largely depend on the ability to resolve spatial and temporal patterns of heat and mass discharge; characterize and quantify the spatial and temporal correlations between tectonic, magmatic, and climatic processes; and link instrumental signals to source processes. Hopefully, addressing some of these issues will improve current estimates of the various hazards posed by hydrothermal activity, provide a framework for understanding life in extreme environments, and guide the protection and preservation of the unique and diverse thermal features in Yellowstone. YS

*http://onlinelibrary.wiley.com/doi/10.1002/2014RG000452/abstract

Shaul Hurwitz is a research hydrologist for the U.S. Geological Survey in Menlo Park, CA. He studies the dynamics of hydrothermal systems at volcanoes throughout the U.S. and abroad.

Jake Lowenstern is a research geologist at the U.S. Geological Survey, studying the chemistry of magmas and their overlying hydrothermal systems. He serves as Scientist-in-Charge of the Yellowstone Volcano Observatory.

Mammoth Microbes & Their Role in Understanding Warming Coral Reefs

Dr. Bruce W. Fouke

A fundamental shift is underway in the natural, physical, chemical, biological, life, and social sciences in response to the recognition that microorganisms play a fundamental role in the co-evolution and healthy functioning of our planet and biosphere. This realization has been shaped by the application of recombinant DNA biotechnology to virtually every aspect of marine and terrestrial environments around the world. These studies have revealed that microorganisms drive key global chemical cycles, comprise over half of all living cellular organic carbon, and contain the overwhelming majority of genetic diversity on our planet. Remarkably, we now understand that the biodiversity harbored by rain forests and coral reefs is dramatically overshadowed by the microbial biodiversity housed in the outermost subsurface of the earth's crust. As a result of these revolutionary insights, scientists are now probing some of the foremost theoretical and practical scientific questions of our time in an entirely new light, including: How have microbial, plant and animal life, and earth co-evolved through geological time? What will future co-evolution yield in the face of ongoing global environmental change? What steps were involved in how life arose on earth and does life exist elsewhere in the universe? What is the next source of sustainable energy? How will the emergence of infectious disease be changed in marine and terrestrial environments as a result of rapid global climate change?

The Fouke laboratory research group at the University of Illinois Urbana-Champaign has undertaken nearly two decades of coordinated research on Yellowstone hot springs, and Caribbean and Pacific coral reef ecosystems. While at first glance these seem like wildly different and unrelated environments, closer examination indicates a host of striking similarities and scientific parallels. The spring water at Mammoth Hot Springs in northern Yellowstone National Park is derived from rain and snowmelt runoff in the Gallatin Mountains that flows down along faults into the rock subsurface. This groundwater under Mammoth is then heated by the Yellowstone supervolcano to approximately 212°F, chemically dissolves deeply buried marine limestones and evaporites called the Madison Formation (approximately 350 million years old), and flows back up to the surface to emerge from vents at a temperature of 163°F. During this hydrologic journey, the Mammoth

Hot Springs water evolves into a salty chemical fluid that is remarkably similar to seawater. Furthermore, much of the limestone rock, called travertine, that precipitates to form the classic terraced steps of Mammoth Hot Springs, are composed of a form of calcium carbonate ($CaCO_3$) mineral called aragonite. This is the same mineral that corals use to precipitate and grow their skeletons in warm shallow tropical seas. In addition, several of the microbes identified in the 77-163°F hot spring vent drainage patterns at Mammoth Hot Springs are similar, and sometimes even very closely related, to the microbes inhabiting coral tissues, coral mucus, and seawater.

Results of our field-based controlled experiments at Mammoth, therefore, are being used to predict how corals will respond to future global warming and associated increases in sea surface temperature. Heat-loving (thermophilic) microbes living at 147-163°F at Mammoth are able to respond to rapid shifts in water flow rate and temperature by changing the rate at which travertine rock is deposited on the floor of the spring outflow drainage channels. Our biogeochemical analyses further suggest that the microbes do this by producing different types of membrane-bound proteins under changing water temperature and flow conditions. These proteins in turn change the level and distribution of cell surface energy that controls the rate at which ions in the spring combine to form a solid travertine mineral precipitate. We are now applying this mechanism derived from Mammoth to establish new interpretations of how density banding in the aragonite skeleton of tropical corals (similar to tree rings) reflects coral response to changing sea surface temperature.

Coral reefs are dynamic marine ecosystems that play a vital role in nearly all aspects of the physical, chemical, and biological realms of the global oceans. The skeletons of corals and other marine organisms accumulate on the seafloor over geological time to form sedimentary marine limestone deposits that are the planet's largest products of biomineralization. In places such as the Bahamas of the Caribbean Sea and the Maldives of the Indian Ocean, tropical reefs can even form limestone accumulations that are 100's of miles in diameter and more than 3 miles in thickness. One of the most pressing concerns associated with global warming is the accurate prediction of how coral reef ecosystems will respond to the coupled effects of increasing sea surface temperature and associated increases in sea level driven by the melting of polar ice. In addition, other environmental changes directly affect coral physiology and health, resulting in coral health degradation and the onset of bleaching, disease, and other impacts. The density bands laid down by corals as they grow over time create a complex yet well-preserved record of simultaneous changes in sea surface temperature and resulting coral physiological response.

The experimental results from Mammoth are now being synthesized and directly applied to more accurately decouple these biological and non-biological processes from the banding record of coral skeletons. Results of this travertine-to-coral correlation will permit better predictions of changes in past and future global sea surface temperature and thus play a central role in shaping long-term policy strategies for climate change. On your next boardwalk hike through the terraces of Mammoth Hot Springs, think of the global reach of the science being conducted in Yellowstone, and consider the absolutely vital roles of stewardship, protection, oversight, and partnership contributed by the National Park Service to global scientific discovery.

YS

Bruce Fouke (pictured on page 75) works at the cross-disciplinary intersection of geology and molecular microbiology (Geobiology), with emphasis on the emergence and survival of Life within the context of dynamic Earth processes. Results have direct application to a wide variety of societal interests that range from energy and human medicine to environmental sustainability and space exploration. Bruce is a professor in Geology, Microbiology, and the Institute for Genomic Biology at the University of Illinois Urbana-Champaign. He serves as Director of the Illinois Roy J. Carver Biotechnology Center.

Research in Yellowstone

Yellowstone National Park is an amazing natural laboratory where research scientists have an unparalleled opportunity to study a wide variety of topics, ranging from biogeochemistry to large carnivores. Research projects are considered as long as the work can be conducted in a way that does not threaten or diminish the resources for which Yellowstone National Park was established. Research projects are not permitted if they adversely impact resources, conflict with other visitor uses, or threaten public health and safety. Research scientists are in close communication with park staff as they develop new research proposals to discuss methods and study design that will follow Leave No Trace principles and maintain park resources in good condition for future scientific investigations.

The Sound of Science

Jennifer Jerrett

YPF YA

It was mid-day and bitter cold, the kind of cold that makes Yellowstone's thermal features look especially dramatic. The steam rising in the Upper Geyser Basin seemed to be freezing in mid-air, creating huge, ephemeral clouds that glittered in the light. I stood on the boardwalk in front of Old Faithful with my microphone at the ready. I was about to record the sound of this iconic geyser, and I was alone.

The solitude of that late-autumn day was exceptional, and it allowed me to notice something for the first time. As the geyser began to erupt, there was a low-frequency rumble that seemed to come from all directions. It was a sound that I felt almost more than I heard, and it reminded me of a great quote by scientist Anne Fernald I once heard on my favorite radio show: "Sound is kind of like touch at a distance.[1]"

Fernald's statement gets at both the properties of sound as well as our relationship to it. The soundscape is an ever-present component of our lives; indeed, it plays an important role for all kinds of creatures (some researchers are even investigating the role of sound for plants.[2]) But like our landscapes, our soundscapes are changing. Things such as climate change and habitat loss can alter species composition, diminishing the rich acoustic environments those species create. And of course, anthropogenic noise can have deleterious effects on both humans and non-human organisms. These kinds of alterations to our soundscapes make it especially important for us to keep listening–not only to the world around us, but to each other, as well.

In a world dominated by visual media, the act of listening might seem a little old-fashioned. But like sound waves that we can feel with our whole bodies, listening can also touch us in other meaningful ways. Think of listening to a good story told around a campfire or having been read to as a child. When we listen in this way, we co-author an extraordinary landscape–one of imagery, context, and metaphor. It's this level of personal participation in the imagination of a story that allows us to connect with it in such a remarkable manner.

We think in stories; our lives are largely made up of a messy hodgepodge of intertwining narratives. Stories allow us to cross boundaries of time, culture, and understanding. When we combine good science with good storytelling, we enjoy a framework of exploration that feels visceral and intimate, a framework in which the data and methods can really come alive.

Through a cooperative effort with the Montana State University Library Acoustic Atlas project, *Yellowstone Science* is developing an audio podcast series for the publication. Highlighting the rich soundscapes and including the resonant voices of the Greater Yellowstone Area, the pieces aim to tell the stories of the region, to add perspective and advance our conversations about the science and complexities of conservation. I hope they will touch you, wherever you are, and help deepen your experience of the remarkable research that takes place in and around Yellowstone.

To listen to the recording of Old Faithful referred to in this article, visit Yellowstone's Sound Library:

go.nps.gov/yellsoundlibrary

[1] "Musical Language." Radiolab. WNYC New York Public Radio. New York, NY: WNYC, September 24, 2007.

[2] Gagliano, Monica. 2013. Green symphonies: A call for studies on acoustic communication in plants. Behavioral Ecology. 24(4):789-796.

Jennifer Jerrett (pictured above) is a science editor, audio producer, and the "Ask a Scientist" tweet-caster for the Yellowstone Center for Resources (#askYellSci). Having lived in some of the most far-flung corners of the planet including Mongolia and Antarctica, she is thrilled to call Yellowstone National Park home.

The Role of Social Science in Predicting Support for Yellowstone National Park

Jake Jorgenson & Dr. Norma Nickerson

As an enduring icon in American history, Yellowstone National Park remains a unique and popular destination for travelers. Even today, visitation numbers continue to grow with over 3 million guests in 2014. However, public funding is decreasing and the changing demographics within the United States place the relevancy of national parks at risk in American society. *Revisiting Leopold* (2012), prepared by the National Park Service Advisory Board Science Committee, stated:

"Cultural and socioeconomic changes confronting the National Park Service are difficult to overstate. These include an increasingly diversified, urbanized, and aging population, a transforming US economy, and constrained public funding for parks."

Without much debate, anecdotal correlations can be drawn between public support and funding for national parks. As support increases, hopefully public funding should follow suit. But, what influences someone to become an advocate for national parks?

Researchers from the University of Montana Institute for Tourism and Recreation Research (ITRR) used the ITRR travel panel along with email lists from the Yellowstone Association (YA), Yellowstone Park Foundation (YPF), and Xanterra Parks and Resorts to investigate previous visitors' current and future likelihood to support Yellowstone. Emails were sent out in June 2014 to the four email lists, as well as a post on the YPF Facebook page with a link to the online questionnaire. In total, 2,854 responses were gathered for analysis. Five key psychological and behavioral characteristics were investigated to explore if these constructs had a role in predicting park support.

Figure 1. Five psychological and behavioral concepts measured to gauge park support.

Support for Yellowstone was measured through two dimensions: direct and indirect measures. Direct measures included donating to YPF, becoming a YA member, spending nights camping or in hotels within park boundaries, and volunteering in Yellowstone. Indirect measures included sharing experiences with others, bringing new visitors to Yellowstone, visiting the park's facebook page, spending nights in gateway communities, and donating to other conservation organizations. These ten variables were rated on a 5-point scale and summated to obtain a 'current park support' and a 'future likelihood' score that ranged from 10-50 points. Finally, five psychological and behavioral concepts were measured, including place attachment (personal connection to Yellowstone), recreation involvement (the importance of recreation to one's life), visitor motivations, geotouristic tendencies (environmentally, culturally, socially-responsible behaviors that aim to preserve authenticity), and autobiographical memory (or memory of the 'self') (figure 1).

The initial results showed moderate support towards Yellowstone with a summated park score of 27.37 out of 50.00 from all survey groups. For the psychological and behavioral traits, visitors who were highly attached, strongly involved in specific outdoor activities, likely to participate in geotouristic behaviors, and possessed high-impact memories from past experiences in Yellowstone were more likely to have higher support. Respondents who were both YA members and YPF contributors were significantly higher in their support and all other dimensions than other respondents. Essentially, the type of experience visitors had at Yellowstone (engaging and memorable) tends to lead to a higher degree of park support by visitors.

Results point to a strong connection between past experiences and a visitor's willingness to support the park. Park managers may be able to elicit more support for Yellowstone by encouraging experiences that engage visitors outside of their personal vehicle. In fact, *Revisiting Leopold* stressed providing 'transformative experiences' to visitors which is in line with our findings that an engaged visitor will prove to become a supportive visitor of the park. While not yet defined, it appears these experiences are memorable, high-impact, and closely resemble some of the sentiments shared by park supporters. Attaching visitors to the park through meaningful experiences may be the best technique to increased support. These meaningful experiences include the unexpected wildlife viewing opportunities, a first time visit to the park, sharing new experiences with family members, and reliving Yellowstone through the eyes of someone who hasn't been there before. Therefore, understanding these experiences is even more critical and will be the focus of additional sociological research in the park during 2015.

Literature Cited

National Park System Advisory Board Science Committee. 2012. Revisiting Leopold: Resource stewardship in the national parks. Washington, DC.

YS

Jake Jorgenson is a PhD candidate in the College of Forestry and Conservation at the University of Montana. He is also a research assistant at the Institute for Tourism and Recreation Research. His research interests are in tourism and protected area management, social psychology, and decision-making processes of travelers.

Norma P. Nickerson is a Research Professor and Director of the Institute for Tourism and Recreation Research (ITRR) at the University of Montana. The ITRR conducts travel research on economic impact of tourism, visitor characterisitcs, market segmentations, and niche studies related to tourism and recreation.

A DAY IN THE FIELD

Butterflies–the Magicians of Yellowstone

Sarah Haas

There are few groups of wildlife that are generally free from controversy and universally liked. Yellowstone is home to several species under the spotlight of mixed feelings: wolves, grizzly bears, bison, lake trout…. One group of species is staying under the radar: butterflies. They elicit feelings of joy and fascination from most spectators. Not only can their flight mesmerize, strewn with brilliant colors and shades; but the mystery of their life story has captivated humans for centuries. In addition to the seemingly magical transformation through pupation, the alteration from a terrestrial lifestyle to one encompassing flight inspires those of us tied to the ground.

Butterflies are truly remarkable. Most people, even if their knowledge of lepidopterology is limited, are familiar with the long-distance migration of the monarch butterfly (*Danaus plexippus*). One of the most extraordinary journeys taken by any species of wildlife, monarch butterflies living east of the Rocky Mountains cycle through multiple generations to take a trip from the northern U.S. to central Mexico, covering thousands of miles. Cues from the environment trigger the migration, including day length, temperature, and a diminishing source of food. Incredibly, the path of migration is not passed on from one generation to the next (due to the short lifespan of the monarch); but each year they somehow instinctively know where they need to go in order to mate, overwinter, and keep the life cycle in motion.

The intrigues of butterflies, unfortunately, have not resulted in extensive study or documentation within

Photo by H. Blake ©

George Bumann (removing butterfly from net) leads a group of enthusiastic students of butterfly ecology in the hills near Mammoth Hot Springs.

A dotted blue rests on a flowering buckwheat plant.

Yellowstone. Limited investigations of butterflies in the park reveal Yellowstone contains monarch butterflies, as well as at least 133 other species of butterflies. With names like "pearly marble," "pink-edged sulphur," and "lustrous copper," one might imagine a world of color and beauty during the short months when butterflies are easy to find. And their season in Yellowstone is indeed short. Butterflies are intimately connected with the phenology, or life cycle, of flowering plants. When the right plants are available, they will attract butterflies. In Yellowstone, peak butterfly activity occurs in mid-July. One method used to monitor trends in butterfly diversity and abundance is through an annual count. On July 12, 2014, I accompanied the 11th annual butterfly count, led by wildlife biologist George Bumann and his Yellowstone Association "*Observing the Butterflies of Yellowstone*" class.

Identifying butterflies in the field is a multistage process, starting with a distance attempt via binoculars, which usually progresses rapidly to netting and handling the specimen with gentle hands and tweezers for an up-close look. George is very adept at this process and guided our scattered but enthusiastic group. Working on the hillside behind the Mammoth Hot Springs Hotel as well as other habitats in the park, the count yielded a total of 37 species and 286 individuals. The most commonly seen species was the European skipper (*Thymelicus lineola*), a nonnative introduced to North America in the early 1900s. The skipper's competition with native species has not been well studied, but does not appear to negatively affect endemic butterflies.

The fact that butterflies have been studied and monitored to a limited extent in the GYE is unfortunate in the face of a changing climate. Some work, such as George Bumann's annual butterfly count, as well as other investigations by a few scientists (e.g., Debinski, Lund, Gompert) will be critical baseline information. Impacts from shifting climate patterns on the timing of the life cycle, movement patterns, overwinter survival, and essential interactions between butterflies and associated nectaring plants are anticipated. Due to the close relationship between butterflies and flowering plants, changes to vegetation communities and weather patterns are likely already having a direct effect on many species.

Conservation planning for butterflies will be challenging with a lack of long-term data from the GYE. As with many species, current and future effects from a changing climate on butterfly communities will reveal themselves over time; and different butterfly species will respond in different ways—some may thrive while others will likely diminish. The intimate link between the short lifespan of most butterflies and the timing of flowering plants may reveal climate change impacts in a more easily detectable timescale as compared with other, longer-lived species. One thing is certain: continued monitoring of butterfly communities in Yellowstone is critical to assist researchers and managers with impact assessments and development of adaptation strategies that may ensure survival for as many of these little magicians as possible.

YS

For a list of the butterflies documented in Yellowstone, please visit:

www.nps.gov/yellowstonescience

Sarah Haas is the Science Program Coordinator at the Yellowstone Center for Resources. Her background is in wildlife biology and she enjoys watching birds and beasts of all kinds...and still believes in magic.

A LOOK BACK

Are Coyotes Fishermen?

Rudolph Grimm, District Ranger

While riding along the Yellowstone River from Gardiner to Cottonwood Creek on January 26, six coyotes were seen and of this number, three were observed sitting on the ice or bank of the river watching airholes or small open spaces in the ice. At that time I could not determine what so intensely engaged the attention of the animals. They would only notice my approach when I arrived within a short distance of them…

On February 4 as I was driving to the waterguaging [sic] station on the Gardiner River near the Wyoming-Montana state line, I noticed a coyote approaching the river bank in what I thought a typical aimless coyote manner. Returning to this spot about ten minutes later after reading the water guage [sic], my attention was drawn to the river bank by the shrill cry of several magpies. Looking closer, I saw a coyote struggling with a large object in the shallow water near the south bank. At first, I thought he had a duck, but upon approaching to the opposite side of the river which is about 40 feet wide at this point, I saw that the coyote had a large fish in its mouth. Alternatingly lifting and lowering his head with the load, he slowly backed up to the bank. Upon reaching the bank, the coyote knelt down on it, doubled up front legs with his hind legs erect and proceded [sic] to consume the fish. I watched him thus for several minutes and then crossed the river on the nearby bridge.

On my approach the coyote dropped the fish, which proved to be a half-consumed Loch Leven trout of about three to four pounds weight. Fang marks on the back of the trout indicated the fish had been caught by the coyote, probably in the shallow water. This would not be a particularly difficult feat for the agile animal. In this he was helped by the numerous flat rocks that project above the water along the shore at the scene of the catch. The healthy appearance of the fish and the large amount of blood on the snow and rocks indicated that it was alive when captured by the coyote.

It is also plausible that when food is scarce for coyotes as at this time, when due to a mild winter the carcasses of winter-killed big game animals are not available, coyotes obtain food wherever the opportunity presents. An occasional fish found in shallow water would be a welcome addition to the coyote larder, and perhaps not too difficult to obtain.

YS

NPS PHOTO

From Yellowstone Nature Notes: 17(1-2), January–February, 1940, 6-7

NEWS & NOTES

12th Biennial Scientific Conference Draws Over 300

The 12th Biennial Scientific Conference on the Greater Yellowstone Ecosystem was held on October 6-8, 2014, at the Mammoth Hot Springs Hotel. The conference theme, "Crossing Boundaries in Science, Management, and Conservation," focused on the challenges and opportunities posed by crossing environmental, disciplinary, and jurisdictional boundaries in the quest to achieve protection of one greater Yellowstone ecosystem. Over 300 participants were involved in the event, including scientists, federal and state land managers, students, and members of the general public.

The conference series, initiated in 1991, is a multi-agency sponsored event encouraging awareness and application of wide-ranging, high-caliber scientific work on the region's natural and cultural resources. It provides a forum for knowledge-sharing and can inspire new researches questions. Several representatives from the media were on-site to cover the 3-day event, which contained over 70 paper presentations in conference sessions and panels, 35 poster presentations, and four keynote talks.

The opening keynote address was given by world-renowned wildlife photojournalist Michael "Nick" Nichols, who shared some of his stories and images from around the world that have led to conservation action. Other keynote speakers included conservationist Craig Groves, senior scientist for The Nature Conservancy, who shared his global experiences to save endangered places. Fire ecologist and University of Wisconsin professor Dr. Monica Turner discussed how climate change is affecting ecosystems of the greater Yellowstone. Southern Methodist University professor, historian, and author Dr. Robert Righter presented the fascinating case study of the Jackson Hole airport and its history with the National Park Service.

Additional conference information, including the conference program, keynote speaker biographies, and links to video and PowerPoint presentations are available online at:

go.nps.gov/gyescienceconference

Beartooth Highway Receives Prestigious National Register Listing

On May 8, 2014, sixty miles of U.S. Highway 212, also known as "the Beartooth Highway," linking the towns of Red Lodge, Cooke City, and Silver Gate, Montana with Yellowstone National Park was listed in the National Register of Historic Places. Now known as the "Red Lodge-Cooke City Approach Road Historic District," the highest elevation roadway in both Montana (10,350 ft.) and Wyoming (10,947 ft.) will be managed to preserve the historic character of the roadway during planning and construction projects to ensure its unique qualities are retained for future travelers.

The road was originally constructed under legislation signed by President Herbert Hoover in 1931 called the National Park Approaches Act after travelers first were documented using the route by automobile in 1915. Charles Kuralt, the noted CBS travel consultant, referred to the Beartooth Highway as "the most beautiful road in America" in his book *Dateline America* (1979).

Modern travelers would find it hard to disagree with Mr. Kuralt when traveling the road today. Over 20 peaks that top 12,000 ft. in elevation are visible from the road corridor along with high mountain lakes, tundra and forest plant communities, and a plethora of wildlife. While the highway is closed to vehicle travel during the winter months, summer travelers topped 170,000 non-resident travel groups in the summer of 2013, according to a study by the University of Montana and the Institute for Tourism and Recreation Research. Winter use was estimated at 16,000 non-resident travel groups for the winter of 2012-2013. Whether using the Beartooth Highway for recreation or an alternate route, the road is a fantastic rooftop journey off the beaten path that is well worth the time.

SNEAK PEEK

"Up & Coming" in *Yellowstone Science*

Photo courtesy of Michael Nichols National Geographic Magazine©

The Remarkable Grizzly Bears of the Greater Yellowstone *An Ecology and Conservation Review*

Grizzly bears once occupied many different habitats from Arctic tundra in northern Alaska to arid regions of the southwestern United States and Mexico, and from the Great Plains west to the Pacific Coast states of Washington, Oregon, and California. Once the transcontinental railroad systems were completed in 1879, livestock production became a profitable enterprise across the expansive western U.S. To protect cattle and sheep, grizzlies were poisoned, trapped, and shot to near oblivion. By the 1920s and 1930s grizzly bears in the contiguous states had been reduced to < 2% of their historical range and by the 1950s were extirpated from most areas outside of Alaska and Canada. The Yellowstone Plateau region of Wyoming, Montana, and Idaho, often referred to as the Greater Yellowstone Ecosystem (GYE), became one of the last refuges for grizzly bears south of the Canadian border. Grizzlies persisted in the GYE because of its large size, remoteness, wilderness character, and the relative safety afforded by protected federal land status over a large portion of the area. In the late 1960s and early 1970s, National Park Service managers made a decision to close open-pit garbage dumps in Yellowstone National Park (YNP) in an effort to reduce bear attacks and bear-caused damage; and the resultant removals of bears involved in those conflicts. During the same time period, state agencies closed garbage dumps servicing gateway communities outside of the park. The dump closures were controversial because of the high grizzly bear mortality they caused, eventually leading to the listing of grizzlies as a threatened species in 1975 under the Endangered Species Act.

As a result of the controversy surrounding the dump closures, the National Academy of Sciences recommended formation of a guiding advisory group. The Interagency Grizzly Bear Study Team was developed to support independent research on grizzly bear ecology, an approach proven to be extremely successful. The Yellowstone grizzly bear population is one of the best-studied wildlife populations in the world. With 40 years of research and over 100 peer-reviewed scientific journal articles, the Interagency Grizzly Bear Study Team has documented a remarkable growth and expansion of the Yellowstone grizzly population since the dump closures. From 1959 to 1970 prior to dump closures, there were an estimated 234 grizzly bears occupying 14,000-20,000 km^2. The 2014 estimate is at least 750 grizzlies occupying over 50,000 km^2 of habitat. There are more grizzly bears today, occupying a larger area, than there were in the mid-1960s prior to the dump closures.

A telling statistic following the dump closures is the change in the number of bear attacks and property damage events inside YNP. Bear attacks decreased from 49 per year prior to the dump closures to the current rate of just 1 per year inside the park. Similarly, bear-caused property damage incidents declined over that same period from 133 per year to 13 per year following the dump closures. These are notable management accomplishments, particularly in light of an increasing bear population and significantly greater park visitation. Yellowstone and Grand Teton national parks have become the prime grizzly bear viewing destinations in the lower 48 states, contributing millions of dollars to local economies annually.

For four decades, grizzly bear management in the GYE has been informed by the unique research collaboration among federal, state, and tribal agencies, and cooperating universities. In the next issue of *Yellowstone Science*, exciting results of this research will be presented. Recent research findings will include grizzly bear range expansion into areas unoccupied for decades, population estimates and trends, the influence of whitebark pine decline on fall habitat use and grizzly movements, evidence of density dependent effects on the current grizzly population, incidents of cub adoption among related mother bears, the remarkable dietary breadth of GYE grizzly bears–including use of army cutworm moths at remote talus sites–and the challenges of managing habituated grizzlies in national parks.

COMING SOON

Yellowstone Bison: Conserving an American Icon in Modern Society[1]

"The iconic bison deserves our best efforts to assure its place on the American landscape. I am grateful to the authors for clearly articulating the issues we face as we collectively determine the future of these animals. The authors have given us a chance to advance our discussions based on a common understanding of the science, culture, and politics surrounding bison."

— From the Preface by Yellowstone Superintendent Daniel N. Wenk

There is a map of North America from William Temple Hornaday's 1889 publication, *The Extermination of the American Bison*, which shows a series of concentric rings; the rings look like a target. The outermost ring draws an expansive circle around much of the continent, reaching from northern Mexico up to southern Canada and from the Rockies all the way to the Appalachians. This was the historic range of the plains bison

[1] White, P.J., R.L. Wallen, D.E. Hallac, and J.A. Jerrett, editors. 2015. Yellowstone bison—Conserving an American icon in modern society. Yellowstone Association, Yellowstone National Park, Wyoming, USA.

(*Bison bison or Bos bison*). The subsequent rings of the target shrink, indicating the bison's contracting range, until, eventually, a tiny circle–a bull's eye–hovers over Yellowstone National Park. The last two dozen animals known at the time hunkered down in Pelican Valley, deep in the interior of Yellowstone.

Hunted to the brink of extinction, today's population of Yellowstone bison has grown to one which fluctuates between 2,500-5,000 animals: a truly wild population that shapes and is shaped by the same ecological processes as the ancestral populations of wild bison of the past. This is the beginning of one of the greatest conservation success stories of our time.

America's story of bison conservation is inspiring, but it is also complex. Like many conservation stories today, it is not without the entanglements that come with managing migratory wildlife across boundaries and the uneasiness of human intervention.

Yellowstone Bison: Conserving an American Icon in Modern Society not only examines the history of bison conservation and management in the United States, but compiles the latest scientific information about Yellowstone bison. Most importantly, the authors discuss both the opportunities for and challenges to plains bison conservation within the Greater Yellowstone Area and across their historic range. The book outlines the multi-jurisdictional partnerships tasked with successful bison management and offers a candid assessment for moving forward with bison conservation. The book is important not only for the information it provides, but for the framework it creates for engendering strong conservation partnerships with diverse stakeholders in modern society.

The book, scheduled to be released in March of 2015, is being published by the Yellowstone Association and will be available in their bookstore and through their website.

SPECIAL THANKS

to the talented photographers who donated their work for this issue: Helen Blake, Chris Boyer, Bianca Klein, Craig Lee, Ashea Mills, Michael "Nick" Nichols, Tom Murphy, Bradley Orsted, and Seth Ward.

If you are interested in donating photography for consideration in our publications, please contact us at yell_science@nps.gov.

Thank you for supporting *Yellowstone Science*

Support for *Yellowstone Science* is provided, in part, by the Yellowstone Association and the Yellowstone Park Foundation.

For more information about these nonprofit organizations, or to make a donation to support the publication of *Yellowstone Science*, please visit their websites.

YELLOWSTONE ASSOCIATION
INSPIRE. EDUCATE. PRESERVE.

www.yellowstoneassociation.org

YELLOWSTONE PARK FOUNDATION
EST. 1996

www.ypf.org

Canon

The production of *Yellowstone Science* is made possible, in part, by a generous grant through the *Eyes on Yellowstone* program. *Eyes on Yellowstone* is made possible by Canon U.S.A., Inc. This program represents the largest corporate donation for wildlife conservation in the park.

Yellowstone Science

Yellowstone Center for Resources
PO Box 168
Yellowstone National Park, WY 82190

Change Service Requested

PRSRT STD AUTO
US POSTAGE PAID
National Park Service
Dept. of the Interior
Permit No. G-83

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

Photo by Bianca Klein ©

Yellowstone Science is available electronically at www.nps.gov/yellowstonescience.

To update your subscription, email yell_science@nps.gov.