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

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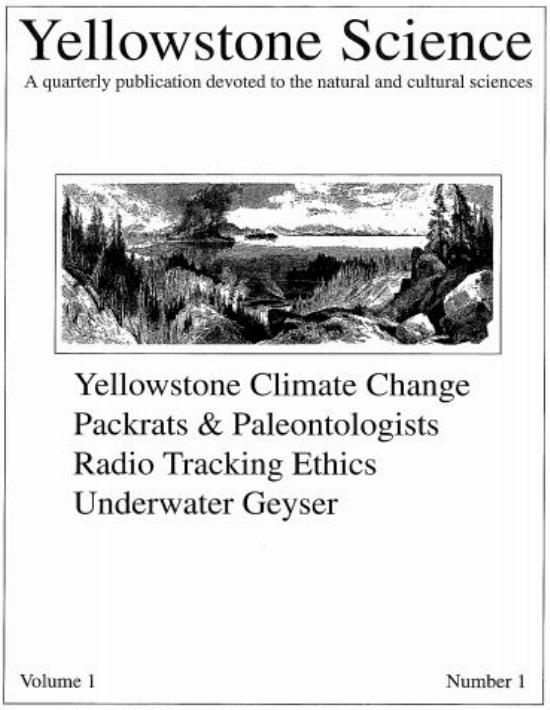
Climate science and understanding how climate change may affect the Greater Yellowstone Ecosystem (GYE) have come a long way since our 1992 *Yellowstone Science* article (Romme and Turner 1992, based on Romme and Turner 1991). In 1992, the potential for global warming driven by anthropogenic emissions 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,



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 post-fire 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.

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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!"