THE COMING CLIMATE

Ecological and Economic Impacts of Climate Change on Teton County

A study by the Charture Institute and the Teton Research Institute of Teton Science Schools

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Executive Summary

Teton County, Wyoming, is a place of spectacular scenery, diverse wildlife, and excellent outdoor recreation opportunities. Every year, more than three million visitors are drawn to the area's natural attractions, while tens of thousands of others make it their first, second, or third home. But in a place where cold weather defines so much of the local ecology and economy, climate change poses an existential crisis for the future. Globally, 2014 marked the warmest year on record – the latest in a series of similar statistics that add to the now virtual certainty that the climate is changing at an unprecedented rate due to anthropogenic greenhouse gas emissions. Locally, in Teton County, temperatures similarly continue to rise. The potential consequences of a changing climate on our ecology, ecosystem services, and economy are numerous and sweeping. In this report, we detail the most current and evidence-based knowledge about the likely and possible impacts of climate change on the Teton region over the remainder of the 21st century.

Changes in temperature and precipitation are already occurring in Teton County and the broader Greater Yellowstone Ecosystem (GYE). For example, average annual temperatures have increased by 1.1° F (0.6° C) since 1900, while stream temperatures have increased by 1.8° F (1.0° C) over the same time period. Frost-free nights are occurring earlier in the spring and later in the fall, and less precipitation is falling as snow (with more falling as rain). These changes are only a fraction of what is expected in the coming decades. Climate models indicate that temperatures in the GYE in 2100 will be on average 3.5° F (1.9° C) to 6.2° F (3.4° C) higher than 1900-2010 baseline temperatures. That is three to six times the warming that has already occurred. Such warming will likely lead to much less snow (both in volume and duration of cover), lower summer stream flows, and increasingly dry forests that are highly vulnerable to fire. The climatic conditions necessary to support mega-fires (on the order of the 1988 Yellowstone fires) are predicted to occur in almost all years by 2100, instead of every 100-300 years. All of these changes would have far-reaching ecological and economic impacts for Teton County and the broader GYE.

Ecologically, some of the likely consequences of these climatic changes include: declines and/or local extinctions among cold- and snow-dependent species such as moose, wolverines, and Canada lynx; declines among native salmonid fish, including Yellowstone cutthroat trout; large-scale declines in forest cover due to frequent fires; replacement of forests with shrubs and grasses, including more invasive species; and generally unfavorable or unlivable conditions for many plants and animals on land and in water. These changes have the potential to radically alter the species composition, scenery, and wild character of Teton County and the GYE.

Economically, these changes are likely to alter the patterns of tourism and visitor-generated revenue substantially. Fewer opportunities to ski, snowmobile, fish, float, or hunt will likely lead to fewer visitors. Winter tourism may benefit for several decades from relatively better snow conditions than other locations in the United States; however, in the long run this benefit is likely to be outweighed by the rising costs of artificial snow production and lost skier days due to lack of snow. The prospect of more frequent fires threatens to reduce summer visitation rates, while the costs of fighting fires (particularly at the growing wildland-urban interface) will likely rise substantially. At the same time, climate change may benefit the real estate business, as more people may choose to make this relatively cool region their home.

The potential consequences of climate change are numerous and far-reaching and understanding them is the first step towards becoming a more prepared and resilient community. We hope that this report will stimulate further discussion and pro-active efforts to mitigate global climate change and reduce its negative impacts on Teton County.

Introduction

The world's climate is changing. 2014 was the world's warmest year on record — the latest statistic illustrating the steady rise in global temperatures that has occurred over the last five decades. The overwhelming scientific evidence now indicates that temperatures will climb at an accelerated rate through the rest of the 21st century unless the global community can take quick action to slow greenhouse gas emissions. Many impacts of climate change are already being seen: glaciers and snow cover have diminished, sea levels have risen, and extreme weather events have become more common. Climate change, once an issue looming in the distant future, is here and now.

Teton County, Wyoming's character and economy are intimately tied to the area's cool climate. Teton County is nestled within the Greater Yellowstone Ecosystem (GYE), one of the largest intact temperate ecosystems on earth. The GYE spans about 20 million acres, including Yellowstone and Grand Teton National Parks, ten wilderness areas, six national forests, three National Wildlife Refuges (including the National Elk Refuge), and state and private lands *(Figure 1)*. Teton County itself encompasses all of Grand Teton National Park, 40% of Yellowstone National Park, and all of the National Elk Refuge.

Every year, three to four million people visit Teton County. The majority visit in summer to hike, fish, float, catch a glimpse of a grizzly bear or moose, and enjoy the sweeping panorama of the Teton Mountains. In the fall, thousands of elk return to the valley for winter, attracting droves of hunters in pursuit of one of North America's iconic big game species. In winter, visitors flock to the area to enjoy the steep lines and reliable snow at the area's three ski resorts and vast backcountry. Throughout the year, Teton County prides itself as a gateway to two of the nation's most scenic and famous National Parks, a premier ski destination, and a part of a uniquely intact ecosystem teeming with wildlife.

Teton County's tourism economy is heavily dependent on these visitors and seasonal residents. Over the 12 months between August 2013 and 2014, Teton County's economy generated $1.115 billion in total taxable sales, with an estimated 35% to 45% of this attributable to visitors *(Schechter, 2014; Graham, 2014a; Graham, 2014b)*. The area's natural beauty and abundant wildlife make it a highly sought-after place to live or own a second or third home, supporting a vibrant real estate market and related construction sector. In 2013, total real estate sales amounted to $740 million *(Rocky Mountain Appraisals, 2014)*, with construction and retail sales comprising a significant portion of the county's economic activity.

As this report suggests, a warming climate will very likely have major impacts on the ecology and economy of Teton County. In this report, we lay the foundation for understanding the potential implications of a changing climate for Teton County. Our future is likely to consist of shorter, warmer winters, more frequent summer wildfires, and lower late-summer stream flows – all with consequences for recreation and tourism. Rather than treat ecological and economic impacts as separate, we discuss them together, emphasizing the many ways in which our local economy is linked to our local ecology. We emphasize that nothing in the future is certain and that the impacts of climate change can only be estimated with varying degrees of certainty. It is possible that some impacts on certain elements of the ecosystem and economy could be positive. A key element of this study is to outline where and how this might be the case.

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In this report, we also strive to lay out what we don't know alongside what we do know. For example, we know that there is a very high likelihood of significant regional climatic changes (e.g. changes in temperature) and that these are highly likely to drive basic changes such as reduced depth and duration of snowpack, reduced summer stream flows, and summer conditions more conducive to wildfire. We know less about how the ecosystems of Teton County might adapt or change in response to these changes. And we know very little about the overall economic impacts of climate change. This is because consumers make decisions based on the choices available to them. Even if climate change has degraded the ecosystem in and around Teton County, the choice to visit, recreate or live in Teton County may still be the best choice available on a regional or even national scale because other areas have experienced even worse degradation or are relatively worse off. Furthering our knowledge of the impacts of climate change on the ecology and economy of Teton County will require further study and long-term monitoring of key indicators of change.

We begin this report with a brief primer on the current state of knowledge about global climate change. We then turn to the local impacts on Teton County, starting with impacts on local temperature and precipitation patterns. We focus on three major expected impacts (reductions in winter snow, increases in the frequency and severity of wildfires, and changes to summer stream temperatures and flows) and discuss how these changes may impact the ecosystems, ecosystem services, and economy of Teton County. We finish with a brief discussion of some possible mitigation and adaptation measures. Ultimately, our intent is to lay the groundwork for new projects and institutions to help the community of Teton County prepare for the effects of climate change. We see this report as a beginning, rather than an end, and intend this to be the first in a series of annually updated reports. In addition to supplying information, we aim to spur community awareness and interest in climate change – with the hopes of stimulating dialogue and, ultimately, action, in Teton County.

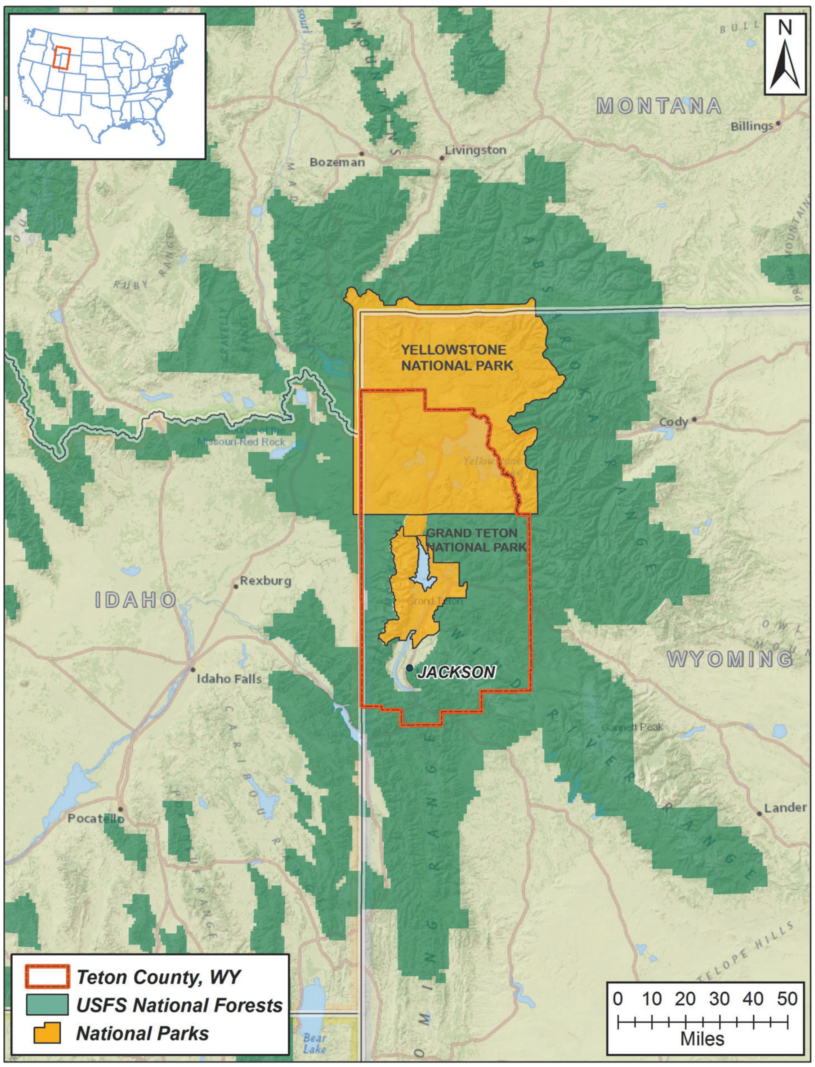
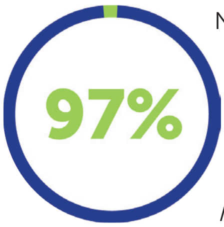


Figure 1

Map of the Greater Yellowstone Ecosystem and Teton County within it.
(Map: Teton Research Institute, 2015).

1. A Changing Global Climate

1.1 Climate Change Now



Ninety-seven percent of climate scientists now agree, with greater than 95% certainty, that the global climate is warming due to human activities that emit greenhouse gasses into the Earth's atmosphere *(IPCC, 2013; Molina et al., 2014)*. Greenhouse gasses, such as carbon dioxide (CO_2) and methane, contribute to the "greenhouse effect" – or the capacity of the earth's atmosphere to trap the sun's heat instead of letting it radiate out. The greenhouse effect is what keeps the Earth warm enough for us to live on it; but as greenhouse gas levels rise, so, too, does the Earth's temperature.

Atmospheric carbon dioxide has risen substantially over the last 250 years, from a pre-industrial (pre-1750) average of 280 parts per million (ppm) to over 400 ppm in 2014 – with accelerated increase in the past 50 years. In over 800,000 years of Earth's history, CO_2 levels have never been so high *(Lüthi et al., 2008)*; that is, human beings have never experienced this level of carbon dioxide. As atmospheric carbon dioxide has risen, the global average temperature has also risen by 1.4° F (0.8° C) since 1880, an amount of warming that cannot be explained by natural factors alone. In the United States, average temperatures have risen 1-1.5° F (0.6 – 0.8° C) since 1880 *v* Most of this warming has occurred since 1960 *(Figure 2)*.

A warming of 1.4° F (0.8° C) may not sound like a lot – but in global terms it is. Think of the human body: a small change in our internal body temperature can mean the difference between a trip to the doctor and a day at the office. Similarly, a small global average temperature increase can have big consequences. In fact, every 2° F (1.1° C) of global warming is expected to cause a 5-15% decline in crop yields, a 3-10% increase in the amount of rain falling in heavy precipitation events, a 5-10% decrease in stream flows in major river basins, and a 200-400% increase in the area burned by wildfires in the western United States *(National Research Council, 2011)*.

Already many noticeable changes in climate and weather patterns have been observed around the world and here in the United States. Sea ice, glaciers, ice sheets, and snow cover are all declining; sea levels are rising; precipitation patterns are changing; fire return intervals are increasing; and extreme weather events are becoming more common *(IPCC, 2014; Melillo et al., 2014)*. These observations are all consistent with predictions for the future under increased global warming.

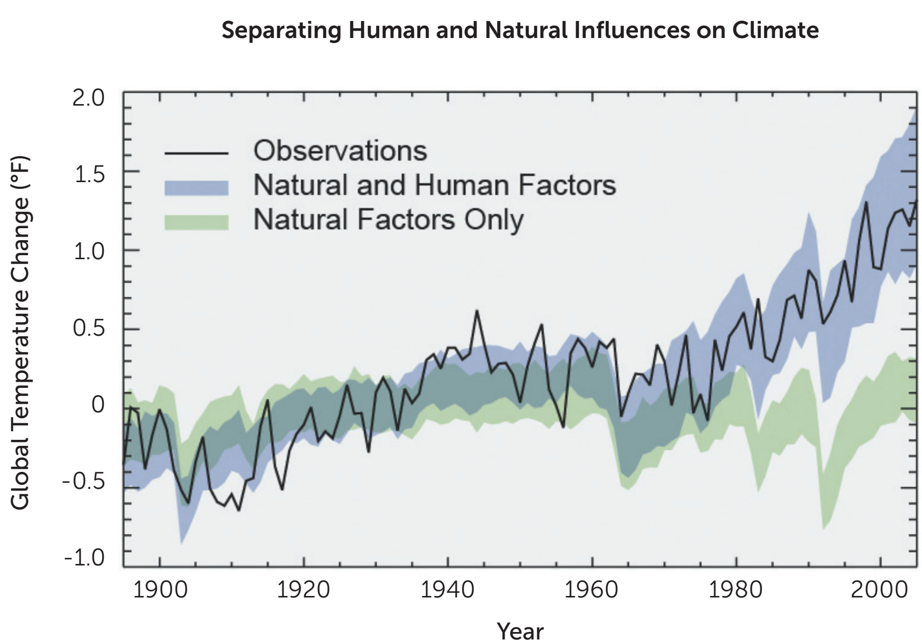


Figure 2

Global temperature change has accelerated since 1960 to levels that cannot be explained by natural factors alone. *(Source: Melillo, Richmond and Yohe, 2014)*.

Global Climate Change in a Nutshell

- Ninety-seven percent of climate scientists agree with > 95% certainty that the climate is warming due to anthropogenic greenhouse gas emissions.
- The global average temperature has risen by 1.5° F (0.8° C) since 1880.
- By 2100, global temperatures are expected to rise by anywhere from 3-10° F (1.7-5.6° C), depending on global CO_2 emissions between now and 2050.
- Even if we stopped all CO_2 and other greenhouse gas emissions right now, we would still see significant warming. Although similar periods of global warming have occurred at other times in the Earth's history, the rate of change we are experiencing right now is unprecedented. This rate of change allows little time for our ecological systems, societies, and economies to adapt.

1.2 Climate Change in the Future

Global temperatures will continue to rise over the next several decades, even if we cease all greenhouse gas emissions today. By 2050, global temperatures are expected to rise by a minimum of 0.9° F (0.5° C), and likely much more *(IPCC, 2013)*. Global atmospheric temperatures lag behind increases in carbon dioxide concentrations because it takes decades for the world's vast oceans to warm. Consequently, many of the impacts from our actions now will only be felt decades later.

The Intergovernmental Panel on Climate Change (IPCC) has developed a set of four plausible scenarios of future greenhouse gas emissions and warming, based on different "what if" scenarios of economic growth and greenhouse gas emissions regulations. These range from a low emissions scenario (Representative Concentration Pathway – RCP – 2.6) resulting from very aggressive curbing of greenhouse gas emissions, to a high emissions scenario (RCP 8.5) resulting from unmitigated greenhouse gas emissions (business as usual), with two intermediate scenarios (RCP 4.5 and RCP 6). These scenarios are then used to predict global temperature changes between now and 2100. For the purposes of this report, we will focus on RCP 2.6 and RCP 8.5 as low and high emissions scenarios.

Under the lower emissions scenario, global temperatures are expected to rise 3-5° F (1.7-2.7° C) above pre-industrial temperatures by 2100 *(Figure 3)*. Under the high emissions scenario, global temperatures are expected to rise 5-10° F (2.7-5.5° C) by 2100. Predictions for the United States are similar *(Melillo et al., 2014)*.

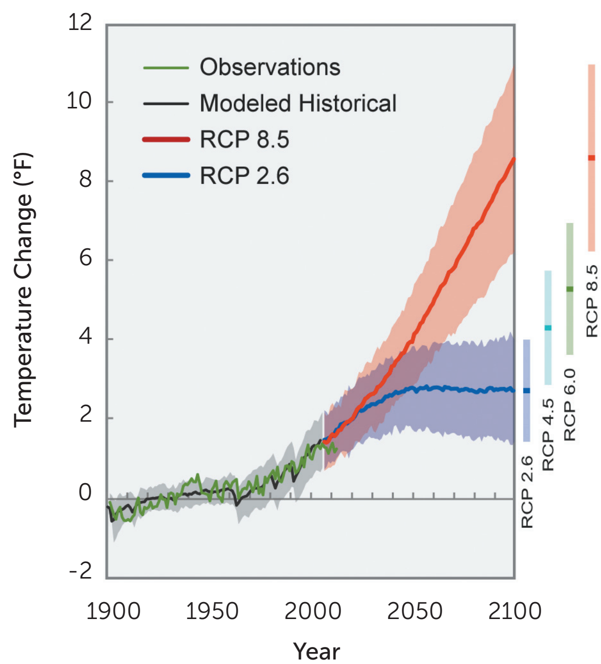


Figure 3

Predicted temperature change under low (RCP 2.6) and high (RCP 8.5) emissions scenarios developed by the IPCC. The high emissions scenario assumes unchecked greenhouse gas emissions over the rest of the 21st century, while the low emissions scenario assumes aggressive curbing of greenhouse gas emissions. *(Source: Melillo, Richmond and Yohe, 2014).*

1.3 Global Impacts of Climate Change

Globally and nationally, the major environmental impacts of climate change include changes in the amount and timing of precipitation; more storms, droughts, heat waves, and extreme weather events; sea level rise; changes in runoff and water availability, including both increased flooding and reduced stream flows; more frequent disease outbreaks; species extinctions; and declines in agricultural productivity *(IPCC, 2014; Melillo et al., 2014)*. Almost all of these impacts have already been observed *(IPCC, 2014; Melillo et al., 2014)*.

Since national and global economies are directly tied to our climate, there are likely to be far-reaching secondary consequences of climate change. Shifts in climate alter our ecosystems in ways that result in economic costs to society. Temperature and precipitation influence how much it costs to heat or cool our buildings, grow crops, and produce products. The frequency and severity of weather events influence how much it costs to repair and replace damaged property. Labor productivity is likely to be impacted as temperatures and humidity levels rise. These costs could accelerate if tipping points, or thresholds beyond which the climate will be permanently altered, have been reached *(Houser et al., 2014)*. On a global scale, there may be further consequences such as political instabilities and conflicts, increased poverty, and mass human movements – all due to diminishing basic resources like food, water, and habitable land.

Predicting the magnitude and nature of future climate change impacts is challenging, because the rate of predicted global warming has no known precedent. Expected temperature changes for the 21st century will occur 10-100 times faster than even the fastest documented periods of climatic change in the past 65 million years *(Diffenbaugh and Field, 2013)*. Unprecedented changes like this often lead to unanticipated outcomes. The mainstream scientific community agrees that there is a significant risk of unexpected, irreversible changes in our climate system – including feedback loops that cause abrupt warming – that could have highly disruptive impacts on our societies and ecosystems *(Molina et al., 2014)*. The extent of future impacts will depend strongly on the amount of future warming we experience; this depends, in large part, on global geopolitical decisions made over the next several years to decades.

How Certain is Climate Change Science?

Some aspects of global climate science are better known than others, which often leads to controversy and misunderstanding. It is important to understand which aspects of climate change science are established, and which are less well known (below adapted from IPCC, 2013).

- **Virtually certain (99-100% probability)**
  - Global temperatures have risen since pre-industrial times.
  - Atmospheric CO^2 levels have risen since pre-industrial times.
- **Extremely likely (>95% probability)**
  - Global temperature increases are due to human emissions of greenhouse gases.
  - Temperatures will continue to rise by at least 0.9° F (0.5° C) even if we cut all greenhouse gas emissions.
- **Very likely / very high confidence (>90% probability)**
  - Changes in number of hot days (more) and cold nights (fewer) are occurring due to climate change.
  - Global climate models can accurately represent global climate dynamics.
- **High and medium confidence (>80% and >50% chance, respectively)**
  - A variety of impacts of climate change are occurring, including changes in local temperatures, extreme precipitation events, sea level rise, loss of glaciers and snow cover, and impacts on local ecosystems.
  - Decisions we make now about mitigating or adapting to climate change will affect the risks of climate change through the rest of the 21st century. Risks of impacts are substantially lower under the lowest future temperature scenarios.
  - High confidence in ability of climate models to predict future climate based on future greenhouse gas emissions scenarios.
- **Less certain**
  - Magnitude of future warming depends on the degree to which greenhouse gas emissions are reduced.
  - Extent and magnitude of impacts of global warming depend on the magnitude of future warming.

2. Climate Change and Teton County

The impacts of climate change on specific places, such as Teton County, can be predicted with varying levels of certainty and specificity. In general, predictions about physical changes (such as temperature and precipitation) have higher certainty and specificity than predictions about the ecological and environmental impacts of these physical changes, which in turn are better understood than the potential economic impacts. Because Teton County's economy is so intimately tied to the environment, however, it is vital to consider the myriad possible ways that climate change could impact both our economy and environment.

In producing this report, we have drawn on several lines of information. First, we use changes (e.g. in temperature and precipitation) that have occurred in Teton County and the GYE over the past several decades as indicators of likely future trends. Second, we draw on other regional models (e.g. downscaled climatological modeling) of future climate conditions for this region. Third, we use studies that have been conducted locally in the GYE and in other parts of the Rocky Mountains, combined with our understanding of the regional ecosystem and Teton County's economy, as a basis for outlining plausible future scenarios for Teton County's ecosystem and economy. By using multiple sources of information and considering multiple possible impacts, we have endeavored to paint as complete a picture as possible.

In the rest of this chapter, we provide a general overview of key climatic changes that have already occurred and are likely to continue to occur. We then provide a brief introduction to Teton County's economy and its relationship to the environment. In the next several chapters, we explore several of the key likely or possible ecological and economic impacts of climate change on this region.

2.1 Warming Temperatures: Historical Trends

Patterns of temperature and precipitation change are generally clustered in space across areas with similar geography. Teton County is geographically part of the GYE, which lies at the eastern edge of the Pacific Northwest biogeographic region. While there are only a few weather stations in Teton County, there are more than 100 stations around the GYE. Individual weather stations can be subject to very local effects, gaps in data, or protocol and equipment changes that enhance or dampen long-term patterns of change. For this reason, we present GYE- and Teton County-wide information alongside data from individual weather stations in Teton County.

In considering temperature changes, it is valuable to look not only at average changes but also changes in minimum and maximum daily temperature. Minimum temperatures (or nighttime lows) govern many important processes such as growing season length, mountain pine beetle population growth rate, and the number of nights that local ski resorts can make snow. Maximum temperatures (daytime highs) impact other processes like fish survival and whether we need to consider installing air conditioning or not.

Across Teton County, annual average minimum temperature has risen by 1.3° F (0.7° C) since 1948; most of this warming occurred since 1980 *(Figure 4a)*. Annual average maximum temperature has also risen by 1.6° F (0.9° C) since 1948. At the very local scale of the Phillip's Bench SNOTEL station on Teton Pass, a similar pattern of warming can be seen since 1989 *(Figure 4b)* . Along with these overall patterns of warming, places like Phillip's Bench and other weather stations around the GYE are showing fewer days with temperatures below freezing *(Figure 5a)* and longer frost-free seasons *(Figure 5b;* frost-free season is the number of days from last spring freeze to first fall freeze). The frost-free season at Phillip's Bench, for example, is about 18 days longer, on average, now than it was in the early 1990s. At the same time, extreme hot temperatures are becoming more common, and extreme cold temperatures less common. At Philip's Bench, recent years have seen 6-7 more unusually hot days than in the early 1990s *(Figure 5c;* unusually hot days are defined by temperatures exceeding the 95^{th} percentile from a 1951-1980 baseline). Although we use the Phillip's Bench station as an example, similar patterns and amounts of change are also being seen at weather stations throughout the GYE *(A. Rodman, personal communication).*

Total precipitation across the GYE has not shown any definitive trend over the past century. However, indices of aridity show that conditions have become increasingly dry over the past 25 years *(Chang and Hansen, in review).* This is due to the effects of warming temperature; warmer temperatures increase evaporation and transpiration (the rate at which plants remove water from the soil and release it into the atmosphere). Thus, warmer temperatures can create more arid conditions even if rainfall stays relatively constant or even increases. In the GYE, these drier conditions are generally occurring in late spring and summer.

Warmer temperatures are also impacting snow depth and duration of snow cover. A winter's cumulative snowfall is typically measured as April 1 snow-water equivalent (SWE) – the amount of water contained within the snowpack on April 1. (Historically, April 1 has been a good approximate date of maximum annual SWE). Between 1960 and 2002, April 1 SWE decreased between 5 and 10 cm (7-15% for most sites) across multiple sites in the GYE *(Mote, 2006)*. This is consistent with patterns across the entire West *(Mote, 2006; Pederson et al., 2011a; Pederson et al., 2011b)*, and in the GYE is caused by warmer winter temperatures (since total winter precipitation has not changed). These same warming conditions are also causing glaciers to shrink in the Tetons *(Tootle, Kerr, and Edmunds, 2010)* and in the Wind River Range *(VanLooy and MacDonald, 2014)*, as in virtually all other alpine and arctic regions of the world *(Vaughan et al., 2013).*

CHANGES IN MINIMUM TEMPERATURE IN TETON COUNTY

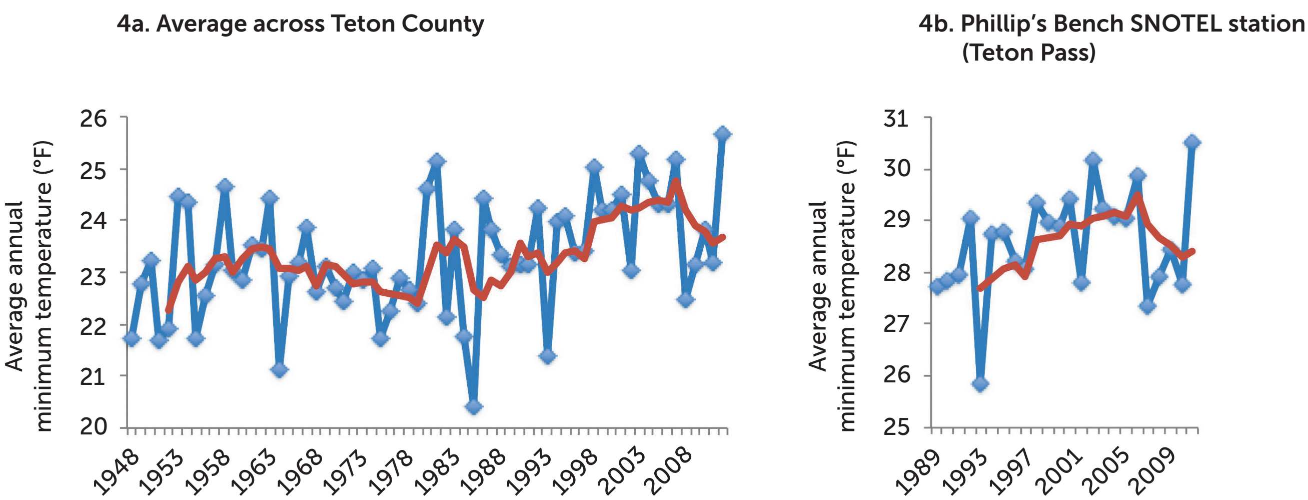


Figure 4

Average annual minimum temperatures (blue line) and five-year running average (red line) for (a) Teton County, and (b) Philip's Bench SNOTEL station on Teton Pass both show marked warming since 1980.
(Data from Yellowstone Center for Resources, derived from the TopoWx dataset described in Oyler et al., in press).

INDICATORS OF LOCAL WARMING ON TETON PASS

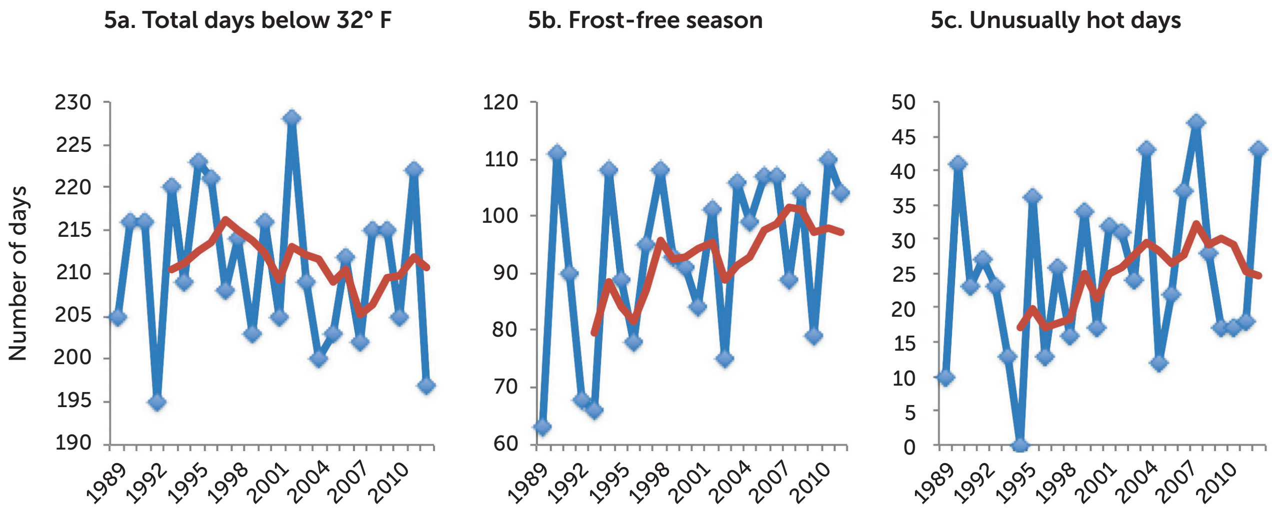


Figure 5

Several indicators of local warming at the Phillip's Bench SNOTEL station on Teton Pass include: (a) Declining number of days with temperatures below 32º F (0º C), (b) Lengthening frost-free season (number of days from last spring freeze to first fall freeze), and (c) Rising number of unusually hot days (temperatures in the 95th percentile based on a 1951-1980 baseline). Blue lines show annual number of days and red lines show five-year running averages. Similar trends are being seen elsewhere throughout the GYE. *(Data from Yellowstone Center for Resources, derived from the TopoWx dataset described in Oyler et al., in press).*

Regional Impacts of Climate Change in a Nutshell

Based on past trends and future models, we can expect that Teton County will see:

- Rising temperatures throughout the year
- Increase in both minimum and maximum temperatures (higher lows and higher highs)
- More winter precipitation as rain
- Shorter duration of snow season; smaller snowpack
- Earlier spring melt
- Drier summers and lower summer stream flows

2.2 Much More Warming: Predictions for 2015-2100

All of the trends that have been seen over the past 20-30 years are expected to intensify considerably in the future. Within the GYE, the best current downscaled climate models indicate that temperatures in 2100 will be on average 3.5° F (1.9° C) (low emissions scenario) to 6.2° F (3.4° C) (high emissions scenario) higher than 1900-2010 baseline temperatures *(Chang and Hansen, 2014)* – three to six times the warming that has already occurred. These increasingly warm conditions can be expected to lead to significantly reduced depth and duration of snowpack (including more areas with transient snow), earlier spring snow melt, lower summer stream flows, and generally more arid summers.

2.3 Impacts on Teton County's Economy

The scenic beauty and abundant wildlife of the GYE are the foundation of Teton County's economy. Over 97% of the county (2,437,243 out of 2,697,257 acres) is public land held by the Forest Service (1,362,960 acres), National Park Service (1,037,570 acres), the Bureau of Land Management (2,913 acres), and the Fish and Wildlife Service (33,800 acres). While the degree of conservation mandate varies among these agencies, all are tasked with some degree of protecting and preserving natural resources. As a result, striking and scenic vistas predominate and wildlife is still abundant in Teton County.

As of July 2013, Teton County's population was around 22,000 permanent inhabitants and had grown by 3% in the previous year *(State of Wyoming Economic Analysis Division, 2014)*. During the peak recreation months of summer and winter, the county's population swells by roughly 25% *(Silbernagel, 2013)*. Meanwhile the county's unique natural attributes draw three to four million visitors to the area each year, making the effective population on any given peak summer season day approximately 60,000 people *(Silbernagel, 2013)*.

In Teton County, visitors and visitation drive a significant amount of economic activity. Visitors to Grand Teton National Park alone are estimated to have generated more than $502 million in economic benefit and supported nearly 7,000 local jobs in 2013 *(Cullinane Thomas, Huber and Kuntz, 2014)*. Accommodation and food services are Teton County's largest employers by sector, with about 6,500 employees as of 2012 *(Bureau of Economic Analysis, 2014)*. This sector also makes up the highest percentage of total compensation paid to Teton County employees. As measured by total compensation, the next largest private sector after accommodation

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and food services is real estate, rental, and leasing, a sector also related to visitation *(Bureau of Economic Analysis, 2014)*. Real estate sales are bolstered by purchases of second or third homes by people who are attracted to the region for many of the same reasons that tourists are.

If visitation declines, there will be fewer visitors making purchases, paying sales tax, occupying lodging rooms, and dining out, leading to reduced economic activity. Employers will cut back on staff, reducing gross economic output even further via the multiplier effect. For example, in 1988, widespread wildfires burned 793,880 acres of forest in and around Yellowstone National Park. As a result, visitation that year dropped from 2.3 million to 1.7 million visitors *(Polzin, Yuan, and Schuster, 1993)*. The resulting loss in tourist-based expenditures amounted to an estimated $21 million in 1988 alone, and another $39 million in subsequent years.

Although the links between visitation rates and the Teton County economy are clear, what is less clear is how climate change might impact visitation rates and the real estate market. In summer, high temperatures in other parts of the country may increase the appeal of Teton County's relatively cooler climate. In winter, more rapid change in other areas (e.g., poorer ski seasons in other parts of the country) may make Teton County a relatively better place for winter recreation. Winter warming may also attract residents who may not have chosen to live here in the past. For example, in January 1979, the temperature in the town of Jackson dipped to -50° F; however, this kind of extreme cold is likely a thing of the past. Taken together, these outcomes may increase visitor numbers as well as the residential population of Teton County and continue to drive economic growth. It is important to acknowledge these potential positive economic impacts of climate change and understand the degree to which they may be offset by negative impacts – such as decreased quality of skiing conditions or increased frequency of wildfires.

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3. Melting Snow: Impacts on Snowpack and Winter Tourism

3.1 Shorter, Rainier Winters

Warming temperatures in Teton County are likely an early warning of future changes in the duration, extent, and depth of snow. At the Phillip's Bench SNOTEL station on Teton Pass, peak snow-water equivalent has dropped by 4 in (10.1 cm) and April 1 SWE by 1.5 in (3.8 cm) since the early 1980s *(data from Climate Analyzer, 2014)*. At sites in the GYE for which longer-term data exist, significant declines in April 1 SWE have been seen at 70% of snow measurement stations *(Rodman et al., 2014).* Similar trends have been seen elsewhere throughout the West *(Pederson et al., 2011a; Pederson et al., 2011b)*. Continued warming is very likely to have further impacts on winter snow cover and depth. With warmer temperatures, we can expect more winter precipitation to fall as rain rather than snow – particularly at lower elevations. This, coupled with an earlier onset of spring and later onset of fall, will likely translate to fewer total days with snow cover and lower peak SWE for any given elevation. The greatest changes are expected to occur on the shoulders of winter (November and March-April). Between 1979 and 2012, November and March precipitation in Teton County and the adjacent mountainous areas was nearly all snow; by mid-century (2035-2065), precipitation during these months is predicted to be mostly rain *(Klos et al., 2014).*

3.2 Ecological Consequences: Trouble for Snow- and Cold-Dependent Species

Shorter winters with less snow, in an ecosystem whose species are mostly adapted to cope with long, cold, snowy winters, are likely to have myriad ecological consequences. The most direct consequences are for species that depend on snow. A deep and stable snowpack creates insulation against cold air temperatures, and a number of mammal species use this insulation to help them get through the winter. Wolverines, for example, make their spring dens in deep, stable snow *(Magoun and Copeland, 1998; Copeland et al., 2010)*. This insulates their young and protects them from predators. Spring snow cover is one of the only predictors of wolverine range *(Aubry et al., 2007)* and declines in wolverine populations have been correlated with periods of time when stable, deep snow is not available *(Brodie and Post, 2010)*. Declining extent and duration of snow cover is one of the main threats to wolverine populations across their range, including the Tetons *(Peacock, 2011; McKelvey et al., 2011)*, and is one of the main reasons that wolverines are being considered for listing under the Endangered Species Act *(Fish and Wildlife Service, 2010).*


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Pika is another species that depends on snow for insulation. Pika, one of the only vertebrates that is active year-round in the alpine zone, create and use a network of subnivean (under-snow) tunnels to move between their dens and stashed haypiles *(Smith and Weston, 1990)*. The thermal protection of a consistent snowpack >50 cm deep protects them from exposure to extremely cold and highly variable winter temperatures *(Beever et al., 2010; Beever et al., 2013)*. Across the West and in the Bridger-Teton National Forest, pika extirpation and population declines have been linked to higher summer temperatures, low precipitation, and acute cold stress *(Beever et al., 2010)*. Because of these various impacts, pika in the GYE are considered highly vulnerable to climate change *(Northern Rockies Adaptation Partnership, 2014)*.

Canada lynx, which are listed as Threatened under the Endangered Species Act, are also highly adapted to snow. Their large feet enable them to walk over deep snow in the winter and catch snowshoe hare – making up about 96% of their diet *(Squires and Ruggiero, 2007)*. Snowshoe hare are highly sensitive to the timing of snow cover; their


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coats turn from brown to white (and vice versa) at consistent times each year, regardless of the presence or absence of snow, and a mismatch between coat color and snow cover leaves the hare highly vulnerable to predators. Because of their intimate dependence on snowshoe hare, lynx typically live in areas that have at least four months of snow cover *(Gonzalez et al., 2007)*. The Bridger-Teton National Forest, Grand Teton National Park, and Yellowstone National Park are all part of the lynx's limited current range, but lynx are considered highly vulnerable in these areas under a high-emissions warming scenario over the next century since they would likely no longer be able to find adequate snowshoe hare *(Gonzalez et al., 2007).*

In addition to these direct effects, reduced snowpack and shorter winters are likely to have many indirect effects on numerous species and ecological processes. Less snow means that forest, grassland, and shrubland soils will dry out earlier in the summer, with various consequences for the plants that they support and the animals that rely upon these plants. In forested areas, dry conditions also increase the chances of fire. Earlier snow melt from a diminished snowpack means that summer stream flows will be lower, with consequences for the fish that live in those streams. These impacts are all discussed in greater detail in subsequent sections of this report.

One other significant impact of warmer winters – the effects of which are already being observed – is an increase in mountain pine beetle outbreaks and declines among vulnerable tree species such as whitebark pine, limber pine, and lodgepole pine. The mountain pine beetle is a native bark beetle that, under historic conditions, has typically existed in relatively small populations that only kill old and weak trees. Sustained periods of temperatures below -13° F (-25° C) are needed to kill enough beetles to prevent widespread epidemics. In particular, low temperatures in late fall before pine beetles have physiologically hardened to freezing seem to cause higher beetle mortality. However, as low temperatures are becoming less frequent, bark beetle epidemics are becoming more frequent *(Mitton and Ferrenberg, 2012; Creeden, Hicke and Buotte, 2014)*. Further, warmer, drier summers render trees more susceptible to beetle attack *(Bentz et al., 2010; Creeden, Hicke and Buotte, 2014)*. This is leading to large-scale pine tree die-offs across the West *(Bentz et al., 2010).*

In the GYE, whitebark pine, as well as limber and lodgepole pine, are particularly vulnerable to mountain pine beetle outbreaks *(Northern Rockies Adaptation Partnership, 2014)*. A recent survey found that 46% of whitebark pine stands had suffered substantial mortality, whereas only 5% of stands had no evidence of mortality *(Macfarlane, Logan and Kern, 2013)*. In Teton County, significant whitebark pine mortality has occurred in the Gros Ventre Range over the last decade. Whitebark pine is further threatened by the drought stress created by warmer summer temperatures, and long-term predictions indicate that little, if any, of the GYE will be suitable habitat for whitebark pine by 2100 *(Chang, Hansen, and Piekielek, in review)*. Whitebark pine is a key player in the ecology of the GYE; loss of this species would threaten the persistence of the many species of birds and mammals – including Clark's nutcracker and grizzly bears – that rely on its nutritious high-calorie seeds for food.

Climate Change and Winter in Teton County

Key impacts are likely to be:

- Shorter winter season, with earlier spring snow melt and later fall freezes
- More precipitation falling as rain, particularly at lower elevations and in late fall/early winter and late winter/early spring
- Shallower and less consistent snowpack
- Loss of snow-dependent mammal species from some or all elevations
- Less, and earlier, runoff from melted snow, leading to lower summer stream flows
- Fewer days suitable for skiing and other winter recreational activities, particularly in November and March
- Loss of revenue due to lost recreational opportunities

3.3 Economic Consequences: Fewer Winter Recreation Days

Winter visitation and recreation make up a significant portion of Teton County's economy. Over the 2013-2014 winter, there were approximately 700,000 skier-days at Teton County's three ski areas — Jackson Hole Mountain Resort, Grand Targhee and Snow King *(Spencer, 2014)*. Each skier-day is estimated to generate approximately $82.59 in revenue (nationwide data from 2011-2012), suggesting that resort-based skiing in Teton County generates approximately $57,813,000 in direct revenue *(Burakowski and Magnusson, 2013)*. In addition, human-powered backcountry recreation directly contributes over $22 million annually in revenue to the broader region (including Teton County, parts of Eastern Idaho and West Yellowstone, Montana *(Newcomb, 2013)*). The economic contribution to Teton County of other winter recreational activities such as snowmobiling, snow-coach tours, and dog sledding have not been measured; however, anecdotal evidence suggests that they also generate significant economic activity.

These activities are all based on a reliable snowpack and lengthy winter season that typically lasts from around Thanksgiving to the first week of April. Reductions in snowpack and/or the duration of the snow season could result in less of these activities and commensurate decreases in economic output. For example, a study focused on Park City, Utah, found that diminished snowpack levels due to climate change are predicted to result in approximately $120 million in lost economic output (20% off a base of $590 million) by 2030 as skier days decline *(Stratus Consulting, 2009)*. Similar studies have not been undertaken for resorts in Teton County. Ski resorts with financial capacity to increase snowmaking may be able to compensate for shorter winter seasons in the short term. Snowmaking is not a viable option for backcountry winter recreation, snowmobiling and snowcoach tours, giving them less leeway for adaptation.

4. Up in Smoke: Impacts on Fires, Forests, and the Costs of Wildfire

4.1 More Frequent Fires

Across the West, fires have become larger, more frequent, and harder to suppress in the last three decades. This is particularly true in the Northern Rockies and is directly attributable to warming temperatures – not forest management *(Westerling et al., 2006)*. Beginning in the 1980s, there has been a significant increase in the frequency of large fires, with individual fires also burning five times longer *(Westerling et al., 2006)*. This change is closely linked with drier forest conditions due to earlier spring snowmelt and warmer summers. The biggest changes in fire regime have been seen in the mid-elevation forests (5,510-8,500 ft; 1680-2590 m) of the Northern Rockies (e.g. lodgepole pine and spruce-fir forests typical of the GYE). In this area, it is clear that a relatively small difference in spring and summer temperature (1.0° F; 0.5° C) means the difference between a year with or without a large fire (>495 ac; 200 ha in extent) *(Westerling et al., 2011)*.

In other words, just a little bit warmer and drier conditions can "flip the switch" between not-fire-prone and fire-prone conditions. This has significant implications for wildfire occurrence under high emission scenarios with warming projected in the range of 6.2° F (3.4° C) by the end of the century.

In the GYE, the largest and most famous fire season occurred in 1988. That summer, 248 fires started within the GYE. Seven of these became major fires, quickly spreading out of control. In the end, about 1.2 million acres (485,000 ha) burned, including 36% of the acreage of Yellowstone National Park itself. Although some hailed these fires "catastrophic", the 1988 season was well within the pattern of major fires that have occurred every 100-300 years in the GYE over the last 10,000 years *(Millspaugh, Whitlock and Bartlein, 2004)*. Given this pattern, another fire season of this magnitude would not be expected to occur until late in the 21st century, at earliest.

The predictions for the rest of this century, however, are for 1988-type conditions to occur numerous times. Using three different climate models, Westerling and colleagues *(2011)* predict that the climatic conditions necessary to burn an area at least as large as what burned in 1988 will occur one to five times before 2050, under all global emissions scenarios. Further, by 2075 (under a high emissions scenario), conditions would support 1988-sized fires or larger in almost all years. Assuming there were enough fuel to burn, this would mean that all parts of the GYE, including Teton County, would be burned at least every 10 years. This is a dramatically different fire and climate regime than these forests are adapted to. In reality, there may not be enough forest cover left by the 2075 to support large forest fires. If forests are replaced by shrublands and grasslands, fires would probably still occur regularly, effectively preventing forests from returning to those areas.

Climate Change and Fire in Teton County

Key impacts are likely to be:

- Significantly greater risk of wildfire; longer fire seasons with more frequent fires
- Several very large fires (at least as large as the 1988 fires) by mid-century
- By the second half of the 21st century, climatic conditions to support 1988-size fires nearly every year (fires may be less frequent, due to lack of fuel to burn)
- Conversion of the majority of forested areas into grasslands and shrublands
- Loss of habitat for a wide array of terrestrial species
- Enormous costs of suppressing fires, especially at the wildland-urban interface, where 25% of Teton County dwellings are currently located

4.2 Ecological Consequences: Widespread Loss of Forests and Forested Habitat

If the frequency of large fires in the GYE increases as predicted, the consequences will be sweeping and radical. Most of Teton County and the GYE is forested land *(Figure 6)*. However, many conifers (e.g. Engelmann spruce, subalpine fir) are not well adapted to fire and require decades without fire to establish in previously burned areas. Even the most fire-adapted conifers, such as lodgepole pine, need several decades of growth before they produce the quantity of seeds necessary for new seedlings to replace the burned trees. For example, an area that burned in 1988 – and was then colonized by numerous lodgepole pine trees – reburned in 2012; it now has almost no lodgepole pine seedlings *(Romme and Turner, in press).* Since fire return intervals are predicted to be less than 20 years by mid-century for most parts of the GYE, there is a very real chance that coniferous forests will disappear from most areas *(Westerling et al., 2011)*. While aspen might be able to colonize some areas, persistence of aspen is also under threat from rising temperatures and drier conditions as aspen regeneration is favored by cool, moist summer conditions. A more likely scenario is that much of the GYE will be converted to non-forest (grassland and shrubland) vegetation by the second half of the 21st century.

Loss of forests would have far-reaching impacts on a host of terrestrial species as well as ecosystem structure and function. Habitat would be severely reduced for species that only live in forested areas (e.g. Canada lynx, snowshoe hare, American marten, northern goshawks, and several other forest-obligate birds), threatening the persistence of these species in the GYE. Moose depend on a mosaic of habitats but use conifer forests for foraging and thermal cover (particularly shade in summer). Moose range distribution is generally considered to be to be limited to areas with lower summer temperatures and restricted by higher summer temperatures. Moose experience heat stress at temperatures above about 57° F (14° C) in summer and 23° F (-5° C) in winter *(Renecker and Hudson, 1986)*, and exposure to heat stress has been linked to decreased body condition *(van Beest and Milner, 2013)*. The stress effects of heat likely also render moose more susceptible to pathogens. These direct and indirect effects of climate change collectively pose a substantial threat to the persistence of this species in places like Teton County *(Murray et al., 2006).* The predicted loss of forest and increasing summer temperatures combine to make widespread moose persistence in the GYE doubtful. Other species that make use of forested areas – for foraging, security cover (e.g. elk), thermal cover, denning sites and numerous other functions – may be able to persist but with very different ecologies and mixed population responses.

On the other hand, widespread conversion of conifer forest habitat to grassland or shrubland may favor some species such as mule deer, pronghorn and certain bird species. The increased habitat may favor increased populations of these species and open up migration routes that were previously not suitable as dense conifer forest. More open habitat, however, would not favor these species if invasive cheatgrass becomes widespread (a possibility, since cheatgrass would be favored by warmer, drier conditions and more frequent fire; see "Other Ecological Impacts"). Further, dry conditions in general are likely to reduce mule deer and pronghorn populations. The net effect of climate change on grassland and shrubland species depends in large part on the extent of change in both habitat quantity and quality and at present is difficult to predict.

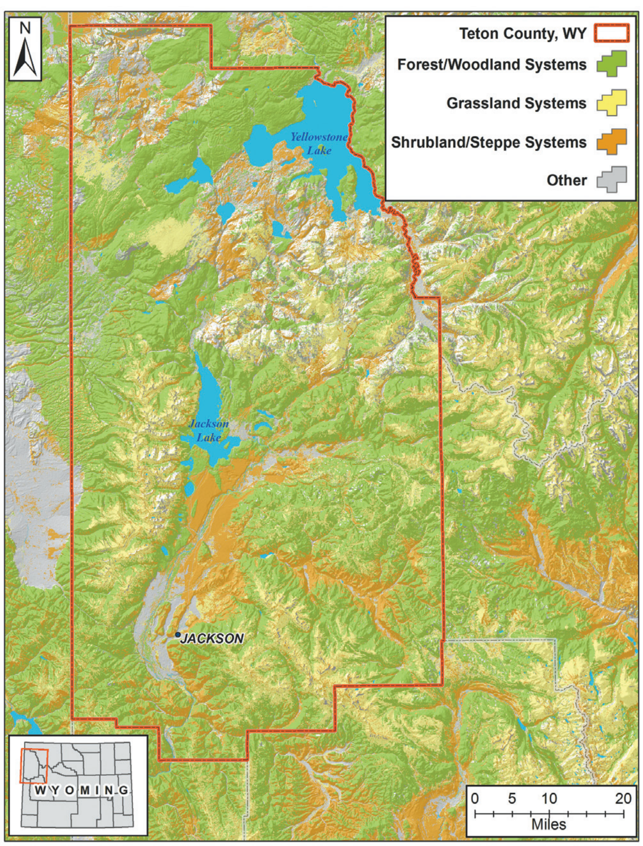

Figure 6

Map of Teton County showing different ecosystem types. Most of Teton County is forested, but forest cover is likely to decrease substantially in the future if fire frequency increases as predicted. *(Map: Teton Research Institute, 2015).*

Loss of forest cover would also exacerbate climate change in two important ways. First, without trees, snow can be expected to melt faster – contributing (above and beyond the effects of warmer temperatures) to earlier spring snowmelt, drier spring and summer soil moisture, and lower summer stream flows. This may be accompanied by increased volume of runoff, since dense conifer forests reduce spring runoff (relative to open areas) by capturing a significant portion of snowfall on tree branches where it sublimates back to the atmosphere during the winter. Second, loss of forests would represent a major loss of carbon storage. Across the West, forests account for 20-40% of U.S. carbon sequestration *(Pacala et al., 2010)*; loss of forests (locally and across the West) would mean much less carbon stored and much more in the atmosphere.

4.3 Economic Consequences

In 1988, the fires in the GYE resulted in more than a 25% decrease in number of visitors to Yellowstone National Park and more than $21 million in lost revenue (out of a total expected revenue of $79.3 million) due to fewer visitors *(Polzin, Yuan, and Schuster, 1993)*. Lower visitation rates persisted for several years after the fires, resulting in another $39 million of lost revenue. If 1988 is any indicator of the future, it is likely that fires will have a substantial negative impact on tourism in Teton County over the next several decades. Long-term change in the scenic value of the landscape (if, for example, large areas of forest are converted to shrublands) may also negatively impact tourism.

The other major economic consequence of wildfires is the cost of fighting them. Since 1985, annual costs of suppressing wildfires in the U.S. have risen from just less than $240 million to over $1.7 billion *(Department of Interior, 2014)*. Wildfire appropriations from the U.S. Congress to the Forest Service have increased from just under $1 billion in 1995 to just under $4 billion in 2014, in part because of an increasing number of structures built in the wildland-urban interface (WUI) that must be defended *(Radeloff et al., 2005; Theobald and Romme, 2007; Headwaters Economics, 2014b)*. The 1988 GYE fires incurred fire-fighting costs of $120 million *(National Park Service, 2014)*, a figure that would likely have been higher if more homes and structures had been directly threatened.

Currently, few of the costs of fighting wildfires are borne by local and county-level agencies *(Headwaters Economics, 2014b)*. For the two largest fires in recent Teton County history that threatened dwellings – the Green Knoll fire in 2001 and the Little Horsethief Canyon fire in 2012 – Teton County government bore almost none of the costs of fighting the fires *(Daigle and Baur, 2014)*. The Little Horsethief fire, however, cost a total of approximately $8 million, $5 million of which was paid for by Federal funds and $3 million of which was paid for by the State of Wyoming *(Watsabaugh, 2015)*. Although no structures were damaged in these fires, the homeowners directly threatened by the fire bore financial costs when forced to evacuate. These kinds of costs can cascade through the local economy, causing a decrease in overall economic output. On the other hand, the presence of non-local fire fighting crews can add to local economic output. However, the evidence from 1988 indicates the former outweighs the latter.

The 1988 fires caused $3 million in estimated property damage within Yellowstone National Park *(National Park Service, 2014*). Although fires in Teton County have not caused large amounts of property damage so far, this is very likely to change as the climate warms. Increasing intensity and frequency of fires along the WUI – both locally and across the West – are expected to threaten more homes while the resources to suppress these fires become increasingly limited and spread thin over disparate geographic areas. In Teton County, there are currently around 3,000 dwelling units located within the WUI (out of a total of about 12,000 units in Teton County), and this number continues to rise *(Headwaters Economics, 2015)*. It is important to emphasize that these homes are expected to come under ever-increasing threat from wildfires under the predicted and plausible scenarios of climate change.

5. Fewer Fish: Impacts on Streams and Rivers

5.1 Warmer, Lower Streams and Rivers

Across the United States, streams and rivers have warmed significantly over the last several decades, in direct correlation with rising air temperatures *(Kaushal et al., 2010; Isaak et al., 2011)*. At the same time, the onset of spring snow melt and peak spring stream flow have shifted earlier by 1-4 weeks across North America, resulting in lower summer stream flows *(Stewart, Cayan, and Dettinger, 2005)*. This has been linked directly to warmer winters and is occurring even in places where precipitation has increased *(Stewart, Cayan, and Dettinger, 2005)*. The predictions for the rest of the 21st century are continued increase in stream temperatures, progressively earlier snow melt, and continued decline in summer and late spring stream flow *(Barnett et al., 2008)*.

In the GYE, stream temperatures warmed by about 1.8° F (1° C) during the 20th century *(Al-Chokhachy et al., 2013)*. Regional climate simulations indicate that stream temperatures in this area will warm by another 1.8°-5.4° F (1-3° C) by mid-21st century (2050-2069), with the greatest amount of warming in July and August *(Al-Chokhachy et al., 2013)*. This level of stream warming was derived by modeling the influence of air temperature on water temperature, but local stream temperatures can be further modified by stream flow levels (lower flow corresponds to warmer streams) and recent history of wildfire (burned areas have less shade and thus warmer streams; *Isaak et al., 2011*). Thus, future stream temperatures could be higher than predicted from air temperature increases alone – especially if there is substantial decline in stream flow or increase in fire frequency or extent..

Climate Change and Streams in Teton County

Key impacts are likely to be:

- Warmer stream temperatures and lower summer stream flows
- Declines in Yellowstone cutthroat trout and other disruptions to cold water stream ecology
- Fewer native fish species to catch
- Possible declines in catch of all fish (native and non-native) due to stream closures implemented by resource managers
- Shifts in the spatial distribution of fishing as fishermen decrease fishing on stressed fisheries and pursue healthy populations along stretches of cooler water
- Possible decrease in overall level of commercial scenic and whitewater trips due to lower and slower stream flows

5.2 Ecological Consequences: Decline in Cutthroat Trout

Warmer stream water is generally bad news for salmonid fishes such as trout. Yellowstone cutthroat trout – icons of and endemic to the rivers of the GYE – flourish in cold water and can only tolerate a small amount of warming. Across its range, Yellowstone cutthroat trout populations are projected to decline by 28% by the 2040s and 58% by the 2080s under high emissions scenarios *(Wenger et al., 2011)*. This is due in part to the direct negative effects of warming stream temperatures, but also because of competitive interactions with non-native brook trout and rainbow trout, which are predicted to fare relatively better under warming conditions *(Wenger et al., 2011; Al-Chokhachy et al., 2013)*. Yellowstone cutthroat trout are food for more than 40 species of predators, including grizzly bears, bald eagles, and numerous other piscivorous birds and mammals *(Stapp and Hayward, 2002)*; loss of cutthroat trout from the GYE would have significant impacts on these species.

Warmer stream waters will also increase the probability of other stream disruptions like eutrophication and establishment of non-native species. Lower stream flows would, additionally, stress riparian vegetation and the associated wildlife they support.

5.3 Economic Consequences: Loss of Fishing and Boating Opportunities

The opportunity to fish in clear mountain trout streams, rivers and lakes brings tens of thousands of visitors a year to Teton County. The goods and services consumed by and the jobs and taxes generated by locals and visitors who fish is significant. In the summer of 2005, it was estimated that there were 61,173 visitors to the stretch of the Snake River between Jackson Lake and the Idaho border, and that these visitors generated 221,337 annual visitor-days and economic activity of $9.5 million related to fishing and $16 million related to boating *(Loomis, Reading, and Koontz, 2005)*. This activity supported an estimated 538 jobs. A study by Loomis and colleagues also found that if anglers caught twice the number of fish or 25% larger fish, they would fish significantly more, generating yet more jobs and more economic value. However the study did not address the effects of a decrease in overall catch or a decrease in the size and quality of fish.

Another study explicitly examined the impacts of climate change on recreational fishing in the Crown of the Continent area in Northwestern Montana. In this study, it was found that the decline of native species, such as the bull trout, led to declines in fishing activity (*Headwaters Economics, 2011)*. Restricted fishing seasons and seasonal closures to protect stressed native species also resulted in less fishing. Restrictions on fishing have periodically been put in place across the West and in the GYE when fish are thought to be stressed by warm weather. For example, in late July, 2007, after a string of record-setting 90° F (34° C) days, around 1,000 trout in the Firehole River died, an event that was linked to the "unnaturally high" water temperatures *(Kinsella, Spencer, and Farling, 2008)*. In late July, 2012, Yellowstone National Park also closed portions of three rivers because of "unusually warm" water temperatures. While unusual at the time, these temperatures may be normal in the future. Fishermen and fishing guide services will likely have to adapt – potentially by reducing the amount of time spent fishing, allowing fishing only for non-native species, or abandoning fishing altogether. Overall this could reduce the economic output related to fishing and other related activities.

Lower and slower stream flows also reduce the number of float trips that can be offered by scenic float operators on the Snake River. While scenic and whitewater float trip operators are reluctant to reveal their numbers, past periods of slower flows have clearly reduced the number of trips an operator can run in a day *(Koshmrl, 2014*). Given predictions for the future, it is likely that float trip operators' peak season will have to shift to earlier in the spring and summer and that they will see an overall decrease in the number of trips they can run per season.

6. Other Possible Impacts

6.1 Other Ecological Impacts

Continued climate change is likely to cause numerous ecological changes beyond those already discussed. A comprehensive account of all the changes that are likely or possible is beyond the scope of this report; however, here and in Table 1 we give some examples of several highly visible and ecologically important changes that are predicted or already being observed. The net picture is one of potentially dramatic and – in most cases – likely irreversible change.

Some significant ecological impacts may include:

- Warming alone – without fire or mountain pine beetles – is expected to cause significant declines in GYE tree species. As a result of reduced spring snow packs and drier summer conditions, high altitude species such as Engelmann spruce and subalpine fir are predicated to see an 85% decline in suitable habitat *(Piekielek, Hansen, and Chang, in review)*, with slightly lower declines in suitable habitat for lower elevation species such as aspen, lodgepole pine, and Douglas fir. Suitable habitat for whitebark pine is predicted to shrink to only 3% of its current range by 2099 *(Chang, Hansen, and Piekielek, in review)*. At the same time, habitat suitability for juniper and sagebrush are both predicted to increase substantially *(Piekielek, Hansen, and Chang, in review)*.

- In addition to altering the composition of native terrestrial plant species, warmer, drier conditions are likely to create favorable conditions for certain invasive species. Cheatgrass is a particular concern because it has invaded large areas of sagebrush across the West and, once established, is extremely difficult to eradicate. Cheatgrass has low forage value and burns very easily, which often dramatically increases fire frequency in invaded shrublands – with the net result of further reducing sagebrush and other co-occurring native species. To date, cheatgrass is not a major problem in Teton County (although it is present in disturbed areas). However, habitat suitability under future climate scenarios is expected to increase substantially in places such as Teton County where cold winters and wet summers have limited its spread *(Bradley, 2009)*. If cheatgrass spreads into the sagebrush-dominated areas of Teton County, it will dramatically decrease habitat quality for sagegrouse, moose, pronghorn, elk, and other species that make use of sagebrush habitat.

- More broadly, but perhaps more subtly, climate change is already impacting numerous terrestrial species by changing the timing of key events, like spring green-up or peak flowering. The timing of flowering has changed markedly in the Rockies *(CaraDonna, Iler, and Inouye, 2014)*, with likely consequences for diverse pollinator species. The timing of spring green-up also appears to be shifting; in the northern GYE, green-up is occurring earlier and more rapidly than in the past, which in turn has been correlated with lower elk calf production rates *(Middleton et al., 2013).*

- The timing and duration of spring green-up is particularly important to migratory ungulates (such as mule deer, elk, moose, pronghorn, and bighorn sheep), which

"track" green-up as they migrate *(Bischof et al., 2012)* and rely on the nutritional benefits of this fresh spring vegetation *(Pettorelli et al., 2007)*. The timing of flowering and green-up is also extremely important to migratory birds, which similarly rely on the plants and insects that are most abundant and nutritious in spring. Birds time their migration using day-length cues, but as the climate changes their migrations are increasingly falling out of sync with the timing of plant growth *(Saino et al., 2011).* This is thought to be one of the main causes of declines among migratory birds across the world. In Teton County, long-term monitoring of migratory songbirds shows a decline in numbers across most species; climate change and mismatched migration timing is one of the possible explanations for this decline *(McCabe, 2014)*.

- Wetlands and ponds are expected to come under threat for the same reason as streams: reduced snowpack and warmer summer temperatures, together leading to lower water levels in summer. Wetlands and ponds do not cover large areas of land in the GYE but are important or critical habitat for many species of waterfowl and other birds, amphibians, and plants. Shrinking or more ephemeral wetlands and ponds would threaten this diversity of species.

It is impossible to predict exactly what the future landscape of the GYE might look like, what species and what ecosystem services this landscape would support. Almost certainly, there will be winners, losers, and changes too numerous to count. In general, ecologists expect that "generalist" species (those with a wide variety of diets or life strategies, tolerant of a wide variety of conditions, and highly mobile or with high reproductive rates) will be favored over more specialized species. Unfortunately, more specialized species include many of those that are already threatened, while generalist species include many non-native or otherwise undesirable species.

Will the GYE in 2075 be a sagebrush and juniper-dominated landscape able to support diverse mammals and birds (some familiar, some new), or will it be a cheatgrass monoculture with very low biodiversity? Much depends on the extent and rate of warming, our ability to take early action to help the ecosystem adapt to a changing climate, and factors beyond anything we can currently imagine.

6.2 Other Economic Impacts

There are many other possible impacts of climate change on Teton County's economy. Although it is difficult to predict all of the impacts, some possible impacts for further investigation include:

- Possible impacts on hunters and hunting due to climate-related changes in ungulate migration and habitat-use patterns or overall population numbers. Elk hunting, in particular, is an important activity not only in terms of attracting visitors to Teton County but also in terms of supplying meat to local residents and revenue to the Wyoming Game and Fish Department.

- More frequent severe weather events such as intense rainfall or strong wind events that impact buildings and infrastructure may result in costly damage and may require additional fire and emergency response services.

- Farmers in Idaho hold the rights to water stored in the Jackson Lake and Palisades Reservoirs. If dry summers forces farmers to rely more heavily on irrigation, this will affect water levels in these reservoirs and flow levels in the Snake River, with potential impacts on recreation.

- If more people seek to visit and move to Teton County because of its relatively more pleasant climate (especially in summer), growth will pressure already scarce housing opportunities and add congestion to already congested roadways. Mechanisms to handle growth, such as public transportation and deed-restricted housing are largely paid for through local taxes shared only in part by visitors.

Table 1

Examples of some of the species likely to be impacted by climate change and the mechanisms of impact.
This table is intended to give a broad overview rather than a comprehensive assessment. Positive impacts on individual plants and animals (which, in many cases, should translate to impacts on populations) are given with + signs and negative impacts with – signs. Where +/- is given, that indicates that an effect could be positive up to a point, then negative (for example, the effect of fire might depend on how much more frequent fires become). Blanks indicate mechanisms that are not likely to have a large impact and question marks indicate mechanisms that are likely to have a large impact but whether the impact will be positive or negative is not yet clear. It is important to recognize that many of these impacts are likely to interact with each other and that it is difficult to assign simple "positive" or "negative" effects in complex ecological systems.

	Less snow	Warmer winters	Warmer summers	Drier summers	More frequent fires; less forested land	Changes in timing of key resource availability	Less runoff from snow
Mammals							
Wolverine	-	-					
Pika	-	-	-	-			
Canada Lynx	-	-					
Moose	+		-	-	-	-	
Mule Deer	+			-	-	-	
Elk	+			-		-	
Pronghorn	+			-		-	
White-tailed Deer			+	+			
Plants							
Whitebark pine		-	-	-	+/-		
Limber pine		-	+	-	+/-		
Lodgepole pine				-	+/-		
Engelmann spruce			-	-	-		
Subalpine fir	-		-	-	-		
Douglas fir			-	-	-		
Aspen		+	-	-	+/-		
Sagebrush and many native herbs and grasses	?			-	-		
Birds							
Sagegrouse				-	?		
Migratory songbirds						-	
Waterfowl				-			-
Fish							
Yellowstone cutthroat trout			-				-
Warm water species			+				+
Invasive species							
Cheatgrass			+		+		
Many other invasive plants			+	+	+		

7. Mitigation and Adaptation

It is easy to feel overwhelmed, despondent, and helpless in the face of such a massive global challenge as climate change. But precisely because the challenge is so considerable, it is important that we begin to think now about what can or could be done. There are two general types of action that we, as a society, can take to combat the negative effects of climate change. The first is mitigation – or reducing the emissions of fossil fuels that are causing climate change. The second is adaptation – or changing the way we manage our resources to minimize the negative impacts and major costs of climate change. Mitigation is largely a global issue – though measures can be taken at a local level to set an important example for others. Adaptation is more of a local or regional issue, depending on the adaptation measure in question.

Climate change at its core is a tragedy of the commons on a global scale — in this case the use of the atmosphere as a dump for fossil fuel emissions. Because of this, it is very difficult to apply the types of systems and institutions that have been used locally to successfully manage common resources. Any long-term effort to mitigate climate change will most likely require two difficult steps. The first is to recognize and quantify, within reasonable levels of certainty, the costs incurred from not reducing emissions into the atmosphere. The second is to incorporate those costs on a global scale in a fair and equitable manner into the consumption of fossil fuels. It is by and large the latter that has impeded meaningful progress towards an international agreement that would reduce the use of fossil fuels and the use of the atmosphere as a dump for fossil fuel emissions on a scale that would prevent substantial alterations of the climate. As individuals and communities, some of the most important steps we can take to mitigate climate change are to support national and international policies to curb greenhouse gas emissions and raise the level of education, awareness, and dialogue about this issue.

At a local level, there are also tangible actions that individuals and local communities can take to adapt to and be prepared for a carbon-constrained future. One course of action is to pursue greater energy efficiency. The other course of action includes implementing policies that give consumers incentives to reduce their reliance on fossil-fuel consuming products and behaviors. Teton County is in a relatively unique position to benefit from gains in efficiency. A substantial portion of the electricity consumed in Teton County is from hydro-power, which costs very little to generate and produces no greenhouse gas emissions. However, once regional demand for electricity exceeds existing capacity, the local utility will be forced to buy electricity from another tier of higher-cost, fossil-fuel based sources, requiring rate increases. Local efforts to improve efficiency aim to avoid rate increases by mitigating 30 megawatts of electricity consumption over the next 20 years *(Energy Conservation Works, 2014)*. Thus, measures such as increasing individual buildings' energy efficiency and increasing use of small-scale renewable energy systems (such as solar) could have a win-win effect of averting costly electricity rate hikes and increases in carbon emissions due to electrical consumption.

Among all carbon-emitting activities in Teton County, transportation accounts for the great majority (79%) of emissions *(Heede, 2009)*. Ground transportation contributes 62% of local carbon emissions and air transportation another

17%. Thus, reducing fossil fuel emissions associated with transportation is one of the most significant measures that can be taken to promote behaviors in line with what is likely to be a more carbon-limited future. Policies that promote public transportation, incentivize use of low-emissions vehicles, and de-incentivize reliance on single-passenger vehicles can help reduce emissions associated with ground transportation. Reducing emissions from air transport is more difficult; however, air travelers can now easily purchase carbon offsets for their trip. Purchasing carbon offsets supports carbon sequestration efforts such as tree planting in deforested areas and promotes the development of emerging carbon-trading markets. Carbon offsets are not a perfect substitute for reducing emissions, but they provide a means for individuals – be they residents or visitors – to take a tangible step towards mitigating climate change.

There are also measures that can be taken to manage our ecological resources and ecosystem services in the face of a changing climate. For ecological systems, adaptation means enhancing the resilience and capacity of species and whole ecological communities to cope with changing conditions. There are some general ecological strategies for promoting the adaptive capacity of species and communities – such as reducing other stresses and promoting greater connectivity in the landscape to enable plants and animals to access new ranges *(Stein et al., 2014)*. In Table 2, we provide some examples of possible adaptation strategies for the GYE. This is not meant to be a comprehensive set of strategies, but rather to suggest the types of actions that might be considered. Careful consideration and, in some cases, further research is necessary before adopting any of these measures as there are almost certainly potential actions that would favor some species or communities at the expense of others. Some measures may be impractical – too difficult or expensive to achieve. In yet other cases, there may be little that can be done to lessen the impacts of climate change; in those situations, we may have little choice but to accept completely new ecological regimes or dynamics for which there is no precedent.

Above all, coping with climate change will require flexibility and creativity. The challenges in front of us are enormous, and exciting, if we can rise to meet them.

Table 2

General strategies for promoting ecological adaptation to climate change *(from Stein et al., 2014),* and some possible examples for the GYE.

General Adaptation Strategy	Examples for GYE
Reduce other sources of stress or other threats (not related to climate change) to these species/ communities.	• Reduce impacts of land development on sensitive wildlife • Reduce surface water off-takes to maintain cooler stream temperatures
Protect areas, species, or processes in the system that are disproportionately important to the functioning of the system.	• Manage keystone species such as whitebark pine (e.g., through planting) • Protect highly species-rich areas or key habitat areas from wildfire • Public education on wildfire management, fuels treatment, anthropogenic fire ignition in the WUI or recreational areas • Maintain tree cover and forest dynamics through wildfire suppression and management of low-severity fires
Maintain or increase connectivity across different habitats and communities (especially along elevation gradients) so that plants and animals can move to new places as conditions dictate.	• Maintain network of protected land • Protect key connectivity corridors through land acquisitions and easements
Restore ecosystem functions where they are degraded. Keeping natural processes as functional as possible helps the system to absorb the stresses of climatic change.	• Restore riparian vegetation to keep streams cool • Enhance post-fire recovery of forested areas through tree planting and/or seeding
Manage for a diversity of genetic material to preserve the potential for species to evolve to changing conditions.	• Protect genetically unique populations • Protect areas with diverse or unique geophysical conditions • Ensure high diversity of any species reintroduced or planted for restoration
Protect "refugia" – places where the impacts of climate change may be less or that can most easily be maintained.	• Protect areas that are less fire-prone or that can be protected from wildfires • Maintain ecological integrity of colder streams
Consider assisting organisms to relocate or establish in new places where conditions are more suitable to them.	• Translocate sensitive or dispersal-limited species to higher elevation areas • Plant species that are more resistant to drought or adapted to fire

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[i] Local geophysicist, Peter Ward, has put forward an alternative theory that ozone depletion is the major cause of climate change. His theory can be explored at https://ozonedepletiontheory.info/. This report is based on the conclusions of over 1,000 scientists as summarized by the Intergovernmental Panel on Climate Change (IPCC).

[ii] We treat RCP 2.6 as broadly equivalent to the earlier IPCC "B1" scenario and RCP 8.5 as broadly equivalent to the earlier "A2" scenario. Much of the research that has been done over the past several years has been based on the earlier B1 and A2 scenarios, rather than the more recent but similar RCP scenarios.

[iii] Although SNOTEL data has recently come under criticism for over-estimating temperature changes, we present data derived from the TopoWx dataset, which corrects for this overestimation *(Oyler et al., in press).*

[iv] Studies focused on single ski areas have two limitations: they do not take into account the ability of ski resorts to adapt by making snow or changing the mix of activities available to guests, and they do not take into account relative changes among all western U.S. resorts. For example, if snow conditions at Jackson Hole Mountain Resort (JHMR) remain on average better than at other Rocky Mountain resorts despite shorter winters, then it might well draw skiers from those areas. If this increase in visitation outweighs any loss of visitors resulting from shorter winters, the overall economic activity in Teton County may actually be higher in the near term than it would have under a no-change scenario. Still, snowmaking is costly as well as energy- and water-intensive and requires so-called "wet-bulb" temperatures (temperature that takes into account humidity) well below freezing. Given the magnitude of plausible increases in winter minimum temperatures, it is uncertain whether increased visitation or snow-making would have a positive impact for more than a few decades.

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