Climate Change Vulnerability in the Black Hills National Forest

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Abstract

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This report was developed to synthesize available information on key climate change issues relevant for management and planning in the Black Hills National Forest in western South Dakota and eastern Wyoming. It summarizes information on historic and current climate and projected future climate change in the region. These projected changes in climate, which include increases in temperature and altered precipitation patterns, will affect ecosystems and associated resources. The vulnerability assessment includes sections on several resource areas, including hydrology and watersheds, fisheries, vegetation, and recreation. The information included in this report is directly relevant to the assessment phase of forest plan revision and can inform the development of plan components.

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Summary

This report synthesizes information on climate change and its effects on key resources on the Black Hills National Forest. Below is a summary of key points from each of the chapters:

Climate change

- Over the last century, the average temperature in the Black Hills region has risen around 2°F.
- By mid-century, mean maximum temperatures are projected to warm 4.3 to 5.3°F with greater warming under RCP 8.5 than RCP 4.5. With warmer temperatures, growing degree days are likely to increase.
- By mid-century, mean minimum temperatures are projected to increase by 4.1 to 5.2°F, with greater warming under RCP 8.5 than RCP 4.5. This warming would result in the mean minimum temperature, historically at 31.7°F in the Black Hills, to rise above freezing by mid-century.
- No significant trends in historical precipitation have been identified, however precipitation for the Black Hills area is projected to increase slightly in the future, reflecting increases projected for the Northern Great Plains.
- The frequency of heavy rain events for the state of South Dakota has increased since 1990. The intensification and frequency of heavy rain events is likely to continue into the future in this region.

Hydrology and watersheds

Climate change will affect hydrology and watersheds by:

- Reducing snowpack and the length of time snow persists
- Increasing the intensity of rainstorms and the potential for flooding in spring and early summer
- Increasing streamflow variability, with some high flow years and some low flow years
- Affecting other disturbances processes, including wildfire and insect outbreaks, which affect runoff and potential for mass wasting.

Fish

- Climate change is expected to alter aquatic habitats in the Black Hills in the 21st century.
- Direct changes are likely to include warmer water temperatures, earlier snowmelt-driven runoff, increased flooding, and more variable summer stream flows, as well as indirect changes caused by shifts in disturbance regimes.

Vegetation

- Projected changes in climate will directly affect forest vegetation in the Black Hills by altering vegetation growth, vigor, mortality, and regeneration. This will affect forest structure, composition, and function, and will have implications for the delivery of ecosystem services.
- Climate change will also have indirect effects on forest vegetation through changes in disturbance regimes and altered ecosystem processes.
- Ponderosa pine, a dominant tree species in the Black Hills, is generally tolerant of drought and fire. However, fires that burn large areas at high severities may present

challenges for regeneration. Insect outbreaks exacerbated by climate change may also make the species vulnerable.

- The Black Hills includes populations of several species at the edges of their ranges. Paper birch and white spruce populations in the Black Hills are both located far south of the remainder of these species' respective ranges, suggesting a high level of vulnerability.

Recreation

- Higher temperatures will extend the duration of the season favorable for warm-weather recreation (nature viewing, hiking, camping, etc.), thus increasing the number of people engaged in warm-weather activities, assuming that roads and facilities are accessible. This will increase stress on facilities and increase demands on recreation staff.
- More extreme-heat days will increase demand for water-based recreation. Lakes where visitation is already high may face increased pressure for access and facilities. Trout populations may be stressed due to more variable stream levels, which may impact angling.
- Increased frequency and extent of wildfires and flooding will reduce access to recreational opportunities and affect recreation infrastructure.
- As snowpack declines in the future, snow-based recreation (snowmobiling, cross-country skiing, downhill skiing,) will have fewer opportunities, especially at lower elevations.

1. Introduction

Thomas J. Timberlake

This report provides a summary of available information on climate change and its effects on key resources associated with the Black Hills National Forest (Black Hills NF). It was developed specifically to support forest plan revision under the 2012 Planning Rule; however, the information in this report is also broadly relevant for programmatic planning and for project-level environmental analysis associated with the National Environmental Policy Act. The report also serves as a foundation for addressing the government-wide priority of tackling climate change outlined in the January 2021 Executive Order on Tackling the Climate Crisis at Home and Abroad (E.O. 14008) and addressing goals outlined in the USDA's Action Plan for Climate Adaptation and Resilience.

The approach used for this report generally follows an established process for developing climate change vulnerability assessments that has been used widely around the western regions of the National Forest System (Peterson et al. 2011), including in the Pacific Northwest Region (Halofsky et al. 2019), Pacific Southwest Region (Halofsky et al. 2021), Intermountain Region (Halofsky et al. 2018a), and Northern Region (Halofsky et al. 2018b). This vulnerability assessment leverages existing information on and models of climate change effects developed for these other vulnerability assessment efforts and draws on information in the Rocky Mountain Region's ecosystem vulnerability assessment (Rice et al. 2018). This initial report was developed based on input and engagement with resource managers with the Black Hills NF and Rocky Mountain Region.

This report was developed using an accelerated version of the process used for other vulnerability assessments mentioned above. As such, it focuses on a set of priority topics identified by resource managers and for which information was readily available. The report does not include information on potential adaptation strategies and tactics. Managers on the Black Hills NF may consider consulting the Adaptation Library that summarizes adaptation actions identified through other vulnerability assessment processes in the western United States. It may also be useful to convene workshops or other engagements focused specifically on identifying adaptation strategies and tactics and to explore potential applications in planning.

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2. Climate Change in the Black Hills

Linda A. Joyce

Introduction

Within the recent historical record, the Black Hills region has experienced extreme temperature ranges, flash flood events, and record hot temperatures co-occurring with severe drought, all affecting natural resources and ecosystem services that flourish in the Black Hills. Understanding the dynamics of historical climate will shed light on the potential effects of projected climatic changes. This chapter reviews the recent historical climate as well as the future climate projections for the Black Hills region. Future changes in climate at the global scale are better understood and have less uncertainty than the fine-scale dynamics of future climate at the scale of the Black Hills region. The experiential knowledge of the Black Hills resource managers combined with the scientific information in this chapter can inform planning, monitoring, and management of natural resources and ecosystem services in the Black Hills National Forest (Black Hills NF).

Black Hills Weather and Climate

The Black Hills region is unique; it is located in the Northern Great Plains and consists of a series of mountain ranges that rise as much as 3,500 feet above the surrounding plains. Both factors influence the Black Hills climate. Frigid Arctic fronts from Canada can bring extreme cold temperatures in the winter to the Northern Plains, affecting the Black Hills NF. While precipitation may come at any time during the year, the warm moist air masses from the Gulf bring most of the moisture in spring. The Arctic frontal system can also interact with these warm air masses, resulting in contrasts of temperature in short periods of time (NOAA 2021a). Typically, the northern Black Hills are influenced by northwest fronts bringing moist air, whereas drier air from the south-southeast influences the southern Black Hills (Stramm et al. 2015).

The elevations of the Black Hills, ranging from 3,800-7,244 feet above sea level (Graham et al. 2021) contribute to generally cooler temperatures in the Hills and winter snow for recreation in contrast to the Great Plains surrounding area. The complex terrain of the isolated mountain ranges within the Black Hills region – the Black Hills, Bear Lodge Mountains and Elk Mountains–influences the spatial variability of precipitation and temperature. Typically, the higher the elevation, the temperatures are cooler with, generally, more moisture. Storm and flood potential in the Black Hills is the smallest in the relatively flat top of the Limestone Plateau, and flood potential increases with topographic relief to the south and north of the Plateau (Driscoll et al. 2010). The eastern and northeast areas of the Black Hills have the largest potential for storms and floods associated with confined canyons and steep topography interacting with the moist air masses from the Gulf of Mexico.

Annual historical climate

The Black Hills NF encompasses three ecoregions: Limestone Plateau-Core Highlands, Black Hills Foothills, and Shale Scablands (Cleland et al. 1997). The highest elevations in the Black Hills region lay within the Limestone Plateau-Core Highlands (Figure 2-1). The Foothills ecoregion surrounds the Limestone Plateau-Core Highlands. The Shale Scablands, at the lowest elevation, surrounds the Foothills, and both ecoregions extend into southwestern South Dakota and northwestern Wyoming. Most of the Black Hills NF lands are in the Black Hills Limestone Plateau-Core Highlands ecoregion, with lesser area in the two other ecoregions.

Figure 2-1. Ecoregions mapped for the Black Hills region: Limestone Plateau-Core Highlands, Black Hills Foothills, and Shale Scablands. Source: EDW EcomapSubsections layer (see National Hierarchical Framework of Ecological Units for more info).

Historical climate describes the broader features of climate of the Black Hills region. Average values for temperature and precipitation, annually or monthly, give an expectation of what the weather could be, while the variability in those means give an indication of how hot or how dry the conditions have been historically. Climate data (1950-2013) for these three ecoregions is provided by Climate by Forest (U.S. Government 2020) based on observations from weather stations within each ecoregion. While the mean maximum temperatures over the 64-year period are similar the ecoregions (Table 2-1), Shale Scablands is the hottest ecoregion, with the Limestone Plateau-Core Highlands having the lowest average maximum temperature of 58.2ºF. The mean minimum temperature in all ecoregions for the 64-year period is just below freezing, ranging from 31.7ºF to 31.9ºF.

The year-to-year annual values of temperature and precipitation show the variability across this historical period (Figure 2-2). The annual maximum temperatures of the three ecoregions track closely (Figure 2-2) with Shale Scablands typically having the hottest mean maximum temperature in any year, followed by the Foothills and then the Limestone Plateau–Core Highlands. The ecoregional patterns for minimum temperatures are not as consistent with Shale Scablands typically having the coldest minimum temperature, but not always. Over the historical period, the coldest minimum temperature was reported in 1951 in all ecoregions, averaging around 28°F (Figure 2-2). The lowest maximum temperature was reported in 1993 when maximum temperatures were 54.3°F in the Limestone Plateau – Core Highlands ecoregion, 54.6°F in Foothills and 54.9°F in the Shale Scablands, nearly 4 degrees lower than the 64-year historical average in each ecoregion (Table 2-1).

Table 2-1. Historical climate averages and ranges for maximum temperature (°F), minimum temperature (°F) and total precipitation (inches) in the three ecoregions in the Black Hills NF. Source: U.S. Government (2020).

	Limestone Plateau-Core Highlands	Black Hills Foothills	Shale Scablands
Mean Maximum Temperature	58.2°F [54.3-62.5]	58.8°F [54.6-63.1]	59.5°F [54.9-64.1]
Mean Minimum Temperature	31.7°F [28.3-34.7]	31.7°F [28.3-34.5]	31.9°F [28.7-34.4]
Total Precipitation	18.4 inches [11.7 – 27.3]	17.3 inches [11.0-25.7]	16.3 inches [10.8-23.7]

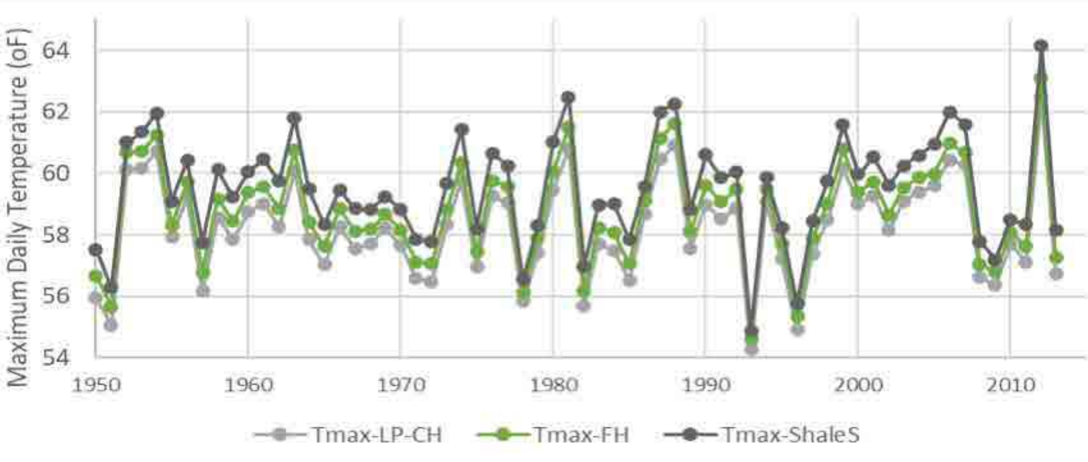
The greatest annual climate variability is seen in precipitation, where total precipitation can range from 10 inches to 27 inches (Table 2-1, Figure 2-2). On average, the Limestone Plateau-Core Highland is the wettest ecoregion with 18.4 inches of total precipitation; the driest ecoregion is the Shale Scablands at 16.3 inches of total precipitation. The three driest years for all ecoregions over the 1950-2013 period were, in order, 1960, 1961, and 2012. Precipitation in 1960 ranged from 10.7 to 11.7 inches, which is 63 to 66 percent of the 64-year annual precipitation in each ecoregion (Figure 2-2). The wettest year for all ecoregions was 1998 with 27.9 inches in Limestone Plateau – Core Highlands, 25.7 inches in the Foothills, and 23.7 inches in Shale Scablands. The second wettest year occurred in 2013.

A critical aspect of reviewing historical climate is to set the historical climate in the context of the consequences to natural resources and ecosystem services. For example, the highest maximum temperature in the historical record occurred in 2012 in all three ecoregions: 64.1°F in Shale Scablands, 63.1°F Foothills, and 62.5°F in the Limestone Plateau-Core Highlands. At the contiguous U.S. area, July 2012 was the hottest month recorded to date in the instrumental record (Karl et al. 2012). Not only were the Black Hills hot, but the region was also in drought conditions in 2012. By September 2012, two-thirds of the contiguous U.S. was in drought with the drought not breaking until 2014, a national scale event that had not been seen in decades (Easterling 2017). The year 2012 was the third driest year in the historical record in all three ecoregions (Figure 2-2). South Dakota as a state also experienced its driest July–September in 2012 with only 2.86 inches of precipitation during the three-month period (Frankson et al.

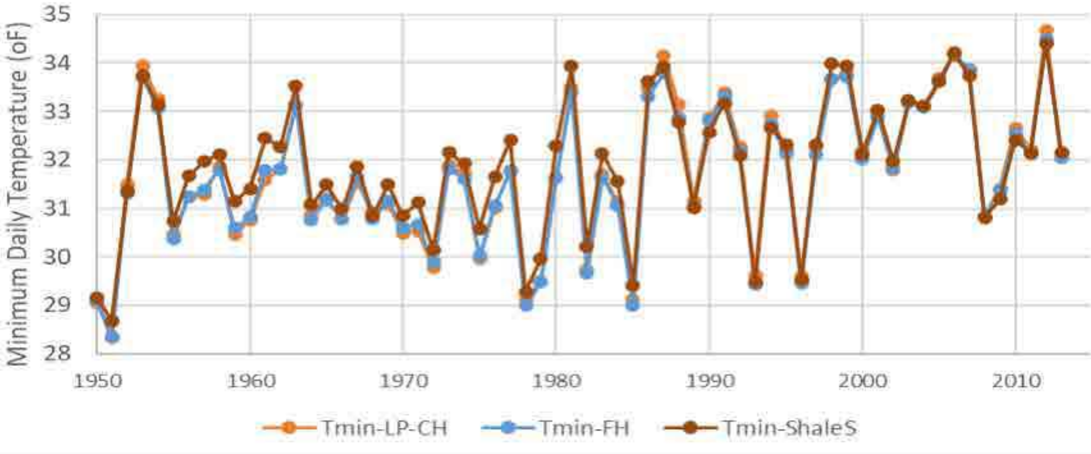
2017). As hot temperatures and drought affected the Black Hills NF, eleven fires were recorded in 2012, including the Oil Creek fire, which at 61,340 acres was the second largest fire recorded up to 2012 on the Black Hills (USFS A1). As will be discussed in later sections, the frequency of these co-occurring climatic events (hot temperatures and drought) is likely to increase.

Figure 2-2. Historical mean maximum temperature (°F), mean minimum temperature (°F), and total precipitation (inches) for three ecoregions in the Black Hills over the 1950-2013 period. Source data: (U.S. Government 2020). Limestone Plateau– Core Highlands: LP-CH, Black Hills Foothills: FH, and Shale Scablands: ShaleS

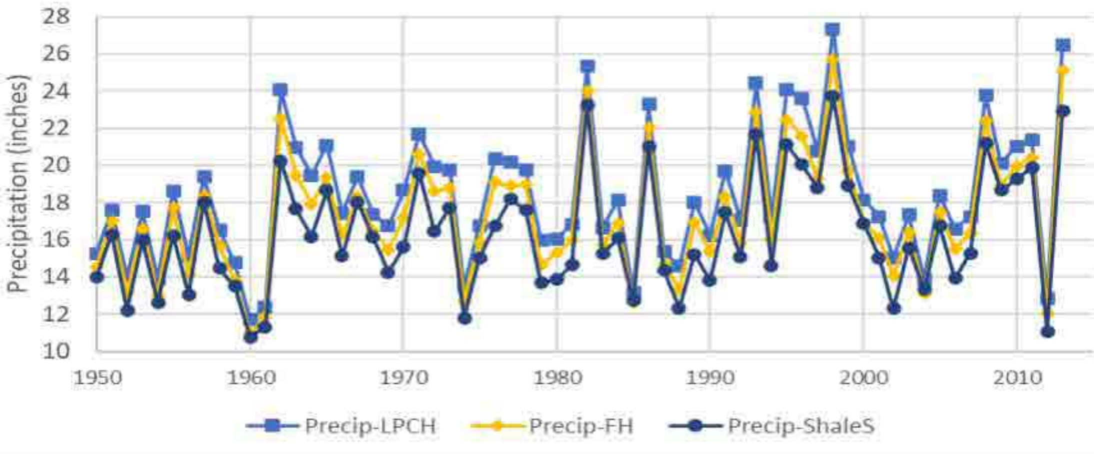
a) Maximum temperature



b) Minimum temperature



c) Total Precipitation



Seasonal climate

Typed as a continental climate, the Black Hills region generally has cold winters and warm summers (Figure 2-3). Precipitation can occur in any month but is generally the greatest in May and June. Flash-flood events have occurred from spring through fall, typically the result of slow-moving thunderstorms or possibly a rain-on-snow event (NOAA 2021b).

The coldest months are January and February with maximum temperatures averaging in the low 30s and minimum temperatures around 10°F (Figure 2-3). Chinook winds and temperature inversions associated with warm Maritime air can produce warmer conditions in winter (NOAA 2021c). Average monthly snowfall ranges from 5 inches in Rapid City on the west of the Black Hills to 15 inches in the Black Hills (NOAA 2021c), however areas in the Black Hills can get up to 70 inches of snow annually (Frankson et al. 2017). The probability of a blizzard occurring anywhere in the state of South Dakota in any given year was estimated at 50% (Frankson et al. 2017).

The snowiest months are March and April, with March snowfall ranging from 15 to 25 inches in the northern Black Hills and 8 to 12 inches over the southern Hills (NOAA 2021c). Mean maximum temperatures range in the lower 40s for March and move into the 50s in April (Figure 3). Minimum temperatures in March are around 20°F and as temperatures warm to the 30s in April, less snowfall occurs in the north (10-20 inches) and the south (5-10 inches) (NOAA 2021c).

Mild weather with thunderstorms characterizes May and June (NOAA 2021c). Temperatures range from the 60s to 70s over these months. While minimum temperatures average in the 40s in May (Figure 2-3), temperatures can drop below 40 (NOAA 2021c). The climate at this time is transitioning from the two snowiest months (March-April) to the two months with the most monthly precipitation (May-June), typically as rain. In the northern Black Hills on May 15, 1965, heavy rain falling on 30 inches of snow resulted in flash floods that impacted Deadwood, Spearfish and Sturgis, resulting in two million dollars (1965 value) in damages (NOAA 2021b). Thunderstorms typically develop over the Black Hills during the afternoon and move onto the plains in the evening. Swartz et al. (1975) described the June 9, 1972 flood as the result of an almost stationary group of thunderstorms over the eastern Black Hills of South Dakota near Rapid City. They reported nearly 15 inches of rain fell in about 6 hours near Nemo and of the 27 streams where peak flows were computed, 18 exceeded the 50-year flood level.

The warmest and driest months are July and August. Precipitation ranges between 1.5 to 2 inches, lower than the monthly averages of May and June (Figure 2-3). Daytime temperatures can rise above 80°F in both months, with minimum temperatures in the 50s. Thunderstorms during these two months produce less rainfall than May and June, and drier conditions increase wildfire potential (NOAA 2021c). While Rapid City records an average of 9 thunderstorms days in August, with only 1.67 inches of rain (NOAA 2021c), intense thunderstorm can result in flooding. Near Hermosa, intense thunderstorms on August 17, 2007 resulted in 10.5 inches of rain, damaging homes, and obstructing highways.

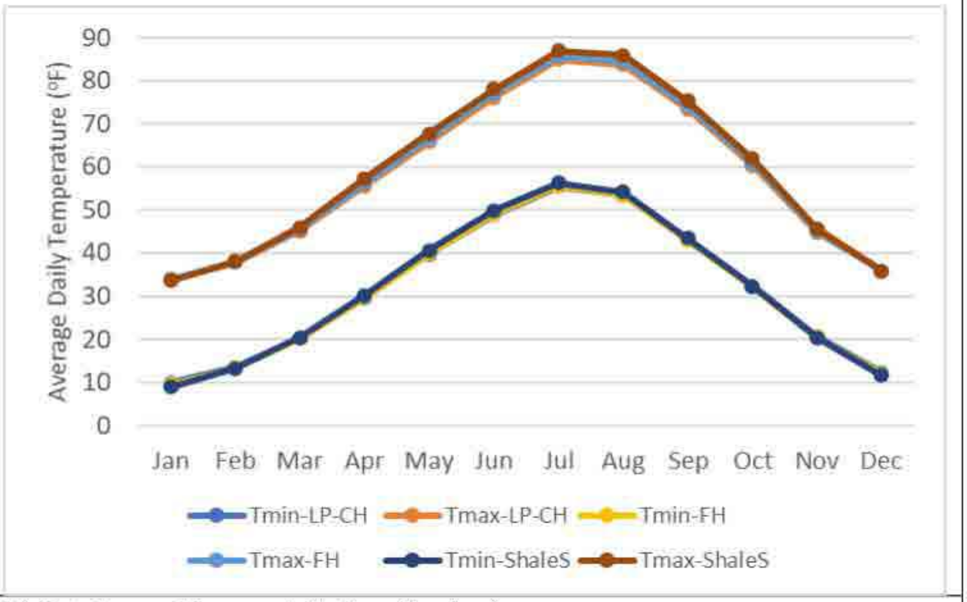
Mild weather with sunny days and cool nights characterizes September and October (NOAA 2021c). September highs are in the 70s for all ecoregions and lows in the 40s, while October is cooler (Figure 2-3). The average first freeze in Rapid City is October 4 and late August through September in the Black Hills (NOAA 2021c). First snowfall is usually in October, although higher elevations sometimes receive snow in September (NOAA 2021c). On

October 3-4 in 2013, the Black Hills and surrounding areas experienced an early season blizzard with high wind gusts (Frankson et al. 2017). Record snowfalls were reported: 55 inches over the 3-day period in Lead; 23.1 inches in Rapid City, the second heaviest snowstorm on record for the city (Frankson et al. 2017). More than 45,000 livestock perished in the storm, with some owners losing more than 90% of their stock (Frankson et al 2017). On October 11-17, 2013, heavy rain falling on melting snow from the October 4-5 blizzard resulted in flooding over the northern and central Black Hills. Flows in Battle Creek were estimated at 1300 cfs compared to normal flows during October of less than 5 cfs (NOAA 2021b).

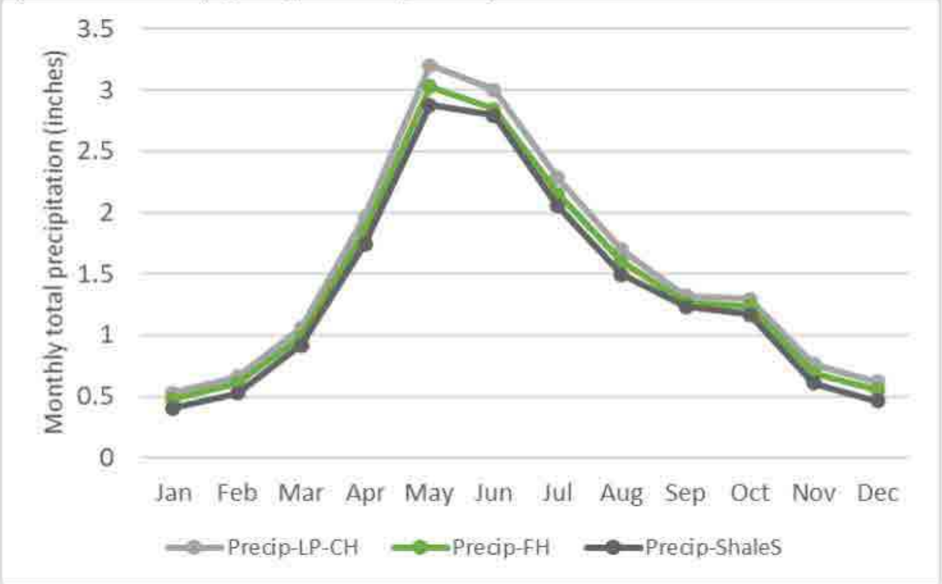
Cold temperatures return in November and December. Maximum temperatures drop below 50°F in November and by December are well into the 30s (Figure 2-3). Mean minimum temperatures are below freezing in both months (Figure 2-3) and can drop below zero (NOAA 2021c). Arctic fronts from Canada will bring below zero temperatures for short periods of time (NOAA 2021c). Snowfall averages about five inches in November and in December with only two days typically receiving more than one inch of snow (NOAA 2021b).

Figure 2-3. Historical mean monthly maximum and minimum temperatures (°F) and total precipitation (inches) for the three ecoregions of the Black Hills over the 1950-2013 period. Source data: Climate by Forest (U.S. Government 2020). Limestone Plateau– Core Highlands: LP-CH, Black Hills Foothills: FH, and Shale Scablands: ShaleS

a) Average monthly maximum and minimum temperatures (°F)



b) Total monthly precipitation (inches)



Trends in historical climate and extreme climatic events

No analyses of historical trends within the Black Hills NF are available, however, historical trends in climate have been analyzed for the region in which the Black Hills NF is located. These studies may focus on different time periods and the region of study may differ. Trends in temperature can be studied as the maximum or minimum temperatures, or number of hot days or days below freezing. Similarly, precipitation trends can be studied in the context of total annual precipitation, seasonal precipitation, and the intensity and frequency of precipitation. Extreme events include intense rainfall events as well as wind events, such as tornados. These analyses provide insights on how climate functions as a system driver for ecosystems, hydrology, and associated human uses in the Black Hills.

Temperatures have warmed over the last 100 years. The increases in average temperature ranged from 1.69°F for the Great Plains North (Montana, North and South Dakota, Wyoming and Nebraska) to approximately 2°F for the state of South Dakota since the early 20th century (Vose et al. 2017, Frankson et al. 2017). Warming in average temperature in South Dakota was concentrated during the winter and spring. Nighttime minimum temperatures in South Dakota were increasing about twice as much as daytime maximums since the early 20th century (Frankson et al. 2017).

Extreme cold events and relative extreme cold events (relative to a season) declined significantly in western South Dakota over the 1980-2016 period (Sheridan and Lee (2018). The number of extreme heat events and relative heat events did not show a significant change in contrast to other parts of the conterminous U.S.

No long-term trends in total annual precipitation were found for South Dakota during the historical period of 1900-2014 (Frankson et al. 2017). Seasonal precipitation also did not show significant long-term trends for the Black Hills region, however other parts of South Dakota had increases in seasonal precipitation (Bromley et al. 2020).

The number of days with precipitation increased in the central Great Plains however the variability was such that the trends were not significant in the Black Hills region, in contrast to other parts of the conterminous U.S. (Bartels et al. 2018).

Recent analyses of heavy precipitation events including the intensity and frequency of such events indicates that these events have increased in both intensity and frequency since 1901 in most parts of the United States (Easterling et al. 2017). Across the Missouri River Basin (which includes the Black Hills region), the 99th percentile extreme precipitation events and the annual station maximum precipitation events became more frequent over the 1950-2019 period (Flanagan and Mahmood 2012). For South Dakota, the frequency of heavy rain events has increased since 1990 (Frankson et al. 2017). Specifically, the number of 1-inch rain events has increased by 14% above the long-term average in South Dakota (historic period 1900-2014). Over central US, these observed increases in springtime total and extreme rainfall are dominated by mesoscale convective systems (MCSs, the largest type of convective storm), with increased frequency and intensity of long-lasting MCSs (Feng et al. 2016). While this process brings increased intensity, it may also be associated with longer dry spells between the extreme events (Dai et al. 2017).

Wind events, such as tornadoes, occur in the Black Hills. At the scale of the conterminous U.S., tornado activity has become more variable, with a decrease in the number of days per year with tornadoes and in increase in the number of tornadoes on these days (Kossin et al. 2017). Confidence in past trends for hail and severe thunderstorm winds at the scale of the US is low, as a tornado is only recorded if seen.

The challenge of analyzing trends in climate is complicated in that other changes are occurring within the region. Land use changes have been suggested as contributing to changes in the local climate responses (Bromley et al. (2020). When streamflow changes were compared with rainfall patterns from nearby weather station measures over the 1951-2013 period in South Dakota, the only streamflow gauging stations in western South Dakota with significant increasing trends in annual streamflow were in the Black Hills region (Kibria et al. 2016). They suggested that these trends in streamflow may reflect increases in precipitation, a finding also reported for the 1904-1993 period by Miller and Driscoll (1998). These gauging stations, Castle Creak near Deerfield Reservoir and Hill City and Battle Creek at Hermosa, had significant increases in annual streamflow over the historical period, however neither station had a significant increasing trend in precipitation. Further examination of the Castle Creek streamflow data suggested to Kibria et al. (2016) that grassland area loss over the historic period may have contributed to the increased streamflow, as soil infiltration capacity is greater in grassland compared to cropland. The role of agricultural intensification in the Northern Great Plains on the local climate has also been studied by Bromley et al. (2020) who suggested local climate changes may be affected not only by the global changes in temperature and precipitation but also by local changes in land use.

Projections of Future Climate

Future projections of climate provide an opportunity to consider what these plausible futures might mean to natural resources and ecosystem services. We draw from the climate projections that were used in the most recent National Climate Assessment (Wuebbles et al. 2017). In that assessment, 32 projections were examined to determine national and regional changes in climate. The approach used in analysis involved the consideration of both skill in the climatological performance of models over North America (how well did the models project historical climate) and the interdependency of models (how similar is model structure and parameterization between the models) (Sanderson and Wehner 2017). All models projected a future climate under two scenarios called Representative Concentration Pathways (RCPs). These scenarios are radiative forcing scenarios – basically the scenarios are constructed by asking if the radiative forcing in the atmosphere by 2100 was +2.6, +4.5, +6.0 and +8.5 watts per square meter (W/m2) more than pre-industrial times, what types of emissions would result in this forcing and then what would happen to the global climate if the atmosphere held this radiative forcing. More details can be found at Hayhoe et al. (2017). For this analysis, the medium forcing (RCP 4.5) and the highest forcing (RCP 8.5) are the scenarios used to project future climate.

Summary statistics from the 32 projections from the Fourth National Climate Assessment are available for all national forests in the Climate by Forest tool (U.S. Government 2020). The projections are summarized to the mean value across all 32 projections for 20 climate variables and on a monthly basis for 3 climate variables. The data available include historical observations, modeled historical projections, and future projections at annual and monthly time periods.

Statistical analysis focuses on determining if the annual changes between a historical period and a future period based on all 32 model projections are statistically significant. Change is computed as the difference between the weighted value of climate variable in future period (2036-2065) and the weighted value of the climate variable from the historical period (1961-1990). This type of analysis determines if the future will be significantly different from the past.

We use the Limestone Plateau-Core Highlands ecoregion to explore historical and future climate of the Black Hills region as it encompasses most of the Black Hills National Forest.

Annual average maximum, minimum temperature, and total precipitation

Mean daily maximum temperature in the Limestone Plateau and Core Highlands area is projected to rise 4.3°F by mid-century under RCP 4.5 and 5.3°F under RCP 8.5 by mid-century (Table 2-2). The increase under the RCP 4.5 scenario would make the mean daily maximum temperature for this future period (2036-2065) nearly the same the mean maximum temperature of 2012, 62.4°F, the hottest observed temperature in the Limestone Plateau – Core Highlands ecoregion. These future projections in maximum temperature are statistically significant from the historical climate of 1960-1990. Average daily maximum temperature increases continually to the end of the century with a greater warming under the RCP 8.5 scenario (Figure 2-4). The mean maximum temperature projections for RCP 4.5 and 8.5 is shown by the solid-colored lines in Figure 2-4. The figure also shows the least warm model projection (lower bound of the color band) and the hottest model projection (upper bound of the color band) of the 32 projections used in this analysis.

The average number of days with maximum temperature over 95°F is projected to increase by 16.1 days under RCP 4.5 and 21.9 days under RCP 8.5 (Table 2-2). The historical average of days over 95°F was 7 days. These projections would result, on average, in tripling the number of days within a year above 95°F to 23 days (or 28 days under RCP 8.5). Historically, the year with the most days above 95°F occurred in 1988 with 17.4 days, and the mean maximum temperature for that year was 2.7°F above the 64-year mean.

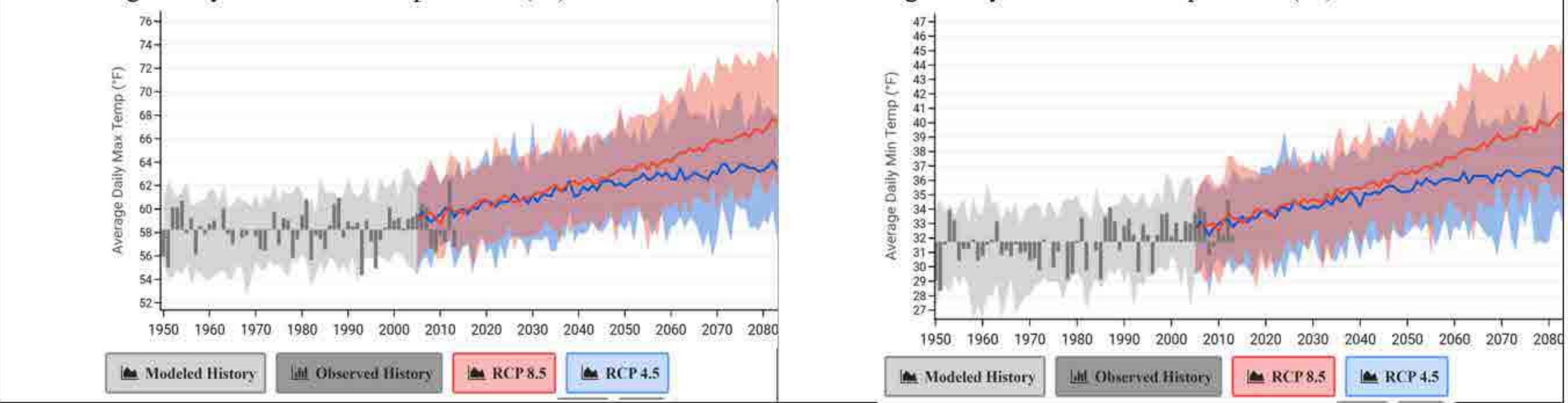
Average daily minimum temperature is projected to increase by mid-century by 4.1°F under RCP 4.5 and 5.2°F under RCP 8.5 (Table 2-2). Given the historical mean minimum temperature of 31.7°F, the projected mean daily minimum temperature at mid-century would be distinctly above freezing. Over the 64-year historical period, the observed mean minimum temperature ranged from a low of 28.3°F to a high of 34.7°F, and was at or above 32°F 26 times, the majority of these occurrences, 23 years, occurred since 1986. The projected minimum temperature continues to rise above the recent history by mid-century and to end of century (Figure 2-4).

Days where the maximum temperature is below 32°F are defining as icing days. The Black Hills region is known for cold temperatures. Historical days below freezing over the 1950-2013 period was an average of 42.2 days each year. The number of days when maximum temperature is below 32°F are likely to decrease 11 to 13 days, under RCP 4.5 and RCP 8.5 respectively (Table 2-2). Projections reduce these days by nearly 25%, to 31 to 29 days. In 1999, maximum temperature was below freezing for 20 days; in contrast, 75 days were below freezing in 1978.

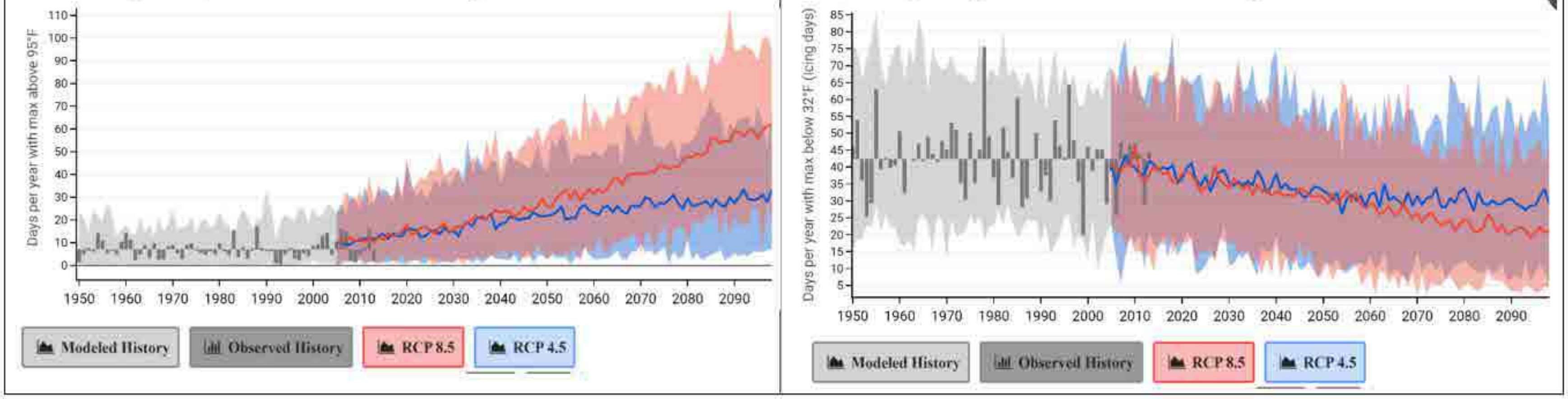
Table 1-2. Projected change in maximum and minimum temperature, days above 95°F, days maximum temperature below 32°F by the period 2036-2065 from the 1961-1990 baseline period under two scenarios (RCP 4.5 and RCP 8.5) for the Limestone Plateau – Core Highlands ecoregion. All changes are statistically significant at the 95% level. Source: U.S. Government (2020)

Black Hills Limestone Plateau and Core Highlands				
Variable	Scenario	Minimum	Mean	Maximum
Average Daily Maximum Temperature (°F)				
	RCP 4.5	3.6	4.3	5.5
	RCP 8.5	4.3	5.3	6.6
Average Daily Minimum Temperature (°F)				
	RCP 4.5	3.6	4.1	4.7
	RCP 8.5	4.3	5.2	6.0
Average Days per Year Maximum Temperature above 95°F (days)				
	RCP 4.5	3.1	16.1	29.3
	RCP 8.5	5.5	21.9	39.5
Average Days per Year Maximum Temperature below 32°F (icing days)				
	RCP 4.5	-10.3	-11	-11.7
	RCP 8.5	-11.8	-12.8	-14.8

Figure 2-4. Historical observations (1950-2013), historical modeled (1950-2005), and future projections (2006-2099) for temperature variables for the Limestone Plateau – Core Highlands ecoregion under RCP 4.5 and RCP 8.5. Source: U.S. Government (2020).


A. Average Daily Maximum Temperature (°F)

B. Average Daily Minimum Temperature (°F)


C. Average Days/Year with Max. Temperature above 95 °F

D. Average Days/Year with Max. Temperature below 32°F

Future projections for precipitation are highly variable, as are the historical observations of annual precipitation (Figure 2-5). At the state level, Frankson et al. (2017) reported that annual precipitation is projected to increase but did not specify amounts. These projections from the recent National Climate Assessment indicate that annual precipitation is projected to increase of 0.6 inches under both scenarios with a projected maximum increase of 1.5 inches by 2050 period (Table 2-3). Between 1950 and 2013, the average total precipitation was 18.4 inches and ranged from 11.7 in 1960 to 27.3 inches in 1998 (Figure 2-5).

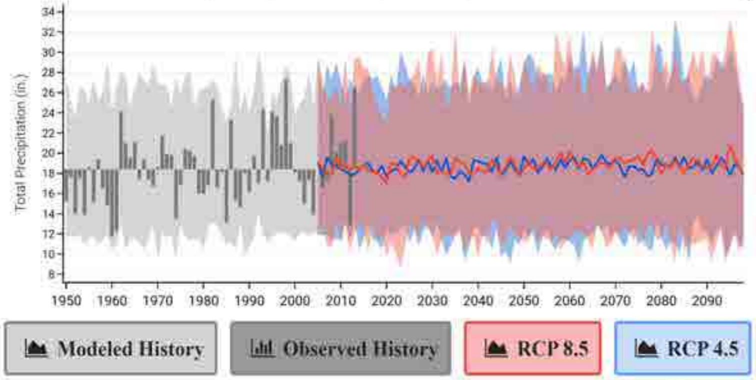
Dry days are the number of days per year when precipitation is less than 0.01 inch. Historically, the average number of dry days was 224.6 days per year and ranged from 189 days in 1982 to 265 days in 1952. Dry days are projected to increase on average by 1.3 days with a maximum projection of 7.1 additional dry days under RCP 4.5 (Table 2-3).

Table 2-3. Projected change in annual precipitation (inches) by the period 2036-2065 from the 1961-1990 period under two scenarios (RCP 4.5 and RCP 8.5) for the Limestone Plateau-Core Highland ecoregion in the Black Hills. All changes are statistically significant at the 95% level, unless noted. Source: U.S. Government (2020)

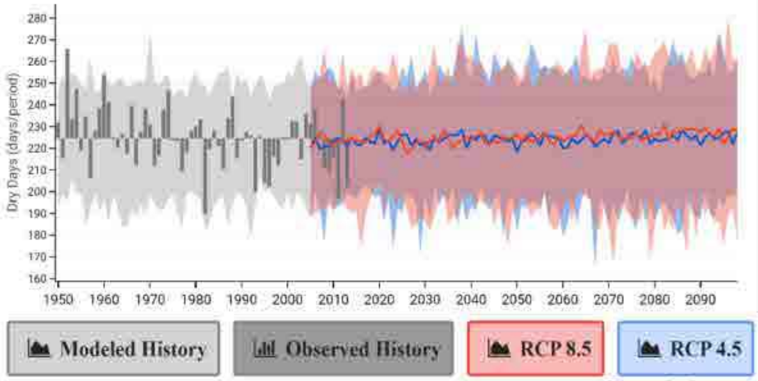
Black Hills Limestone Plateau and Core Highlands				
Variable	Scenario	Minimum	Mean	Maximum
Total Precipitation (inches)				
	RCP 4.5	-0.3NS	0.6	1.5
	RCP 8.5	0.1NS	0.6	1.5
Dry Days (number of days)				
	RCP 4.5	-0.2NS	1.3	7.1
	RCP 8.5	-0.7NS	1.7	6.2

Figure 2-5. Historical observations (1950-2013), historical modeled projections (1950-2005), and future projections (2006-2099) for total precipitation (inches) and average number of dry days (days) for the Limestone Plateau – Core Highlands under RCP 4.5 and RCP 8.5 scenarios. Source: U.S Government (2020).

A. Total annual precipitation (inches)



B. Number of Dry Days (days)



Monthly projections and extreme events

Monthly climate and extreme events have greater historical variability than annual climate data. Consequently, these future projections have more uncertainty than the annual projections. Similarly, extreme events also have greater uncertainty in the future projections of those events.

In all months, the average daily maximum and minimum temperatures increase by the 2050 period (2036-2065). At this point in mid-century, the temperature projections under the two scenarios are similar (Figure 2-6). The two scenarios for maximum and minimum scenario separate toward the end of the century, with greater warming under RCP 8.5.

In the historical period, minimum projected temperatures are below freezing from November through April, with historical October minimum temperature at freezing. By 2050, minimum temperatures are at freezing in April and above freezing in October, with implications to reductions in spring snowpack (see Hydrology section) and potentially a longer growing season.

Historically, monthly precipitation is the greatest in May and June. The projections for monthly total precipitation are very close to the historical values. In addition, the projections are large variation, such that the range (color band in Figure 2-6) of model projections under RCP 4.5 and RCP 8.5 overlaps. There is some suggestion that the winter/spring months could see increased precipitation under both scenarios, with decreasing precipitation in July and August under RCP 4.5 (Figure 2-6). Frankson et al. (2017) conclude that winter precipitation is projected to increase in the Black Hills region (Figure 2-7, see Hydrology section also).

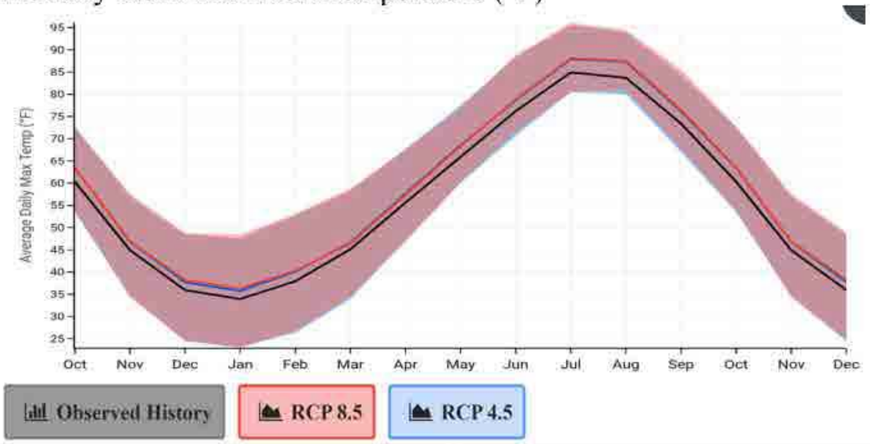
The frequency of heavy rain events in South Dakota and the Missouri River Basin have become more frequent since 1990 (Easterling et al. 2017, Flanagan and Mahmood 2012, Frankson et al. 2017). This intensification is projected to continue into the future (Easterling et al. 2017), with implications to springtime flooding.

Drought is a natural occurrence in the Black Hills region, and the area has experienced serious droughts in the 1930s, the 1950s, and from 2012-2014. Martinuzzi et al. (2016) explored the potential changes in the frequencies of extreme weather – extreme temperature, drought, and false springs for wildlife refuges across the conterminous U.S. Extreme heat is projected to increase in all wildlife refuges based on the historical period (1950–2005) and mid-century (2041–2070) and end-of-century (2071–2100) projections. Wildlife refuges in the Mountain Prairie region which includes the Black Hills did not see an increase in drought as an extreme event, however false springs are likely to increase. The 2012 extreme event in the Black Hills was a combination of extreme heat and drought, with wildfire. Such compound events are likely to increase in the future (IPCC 2021)

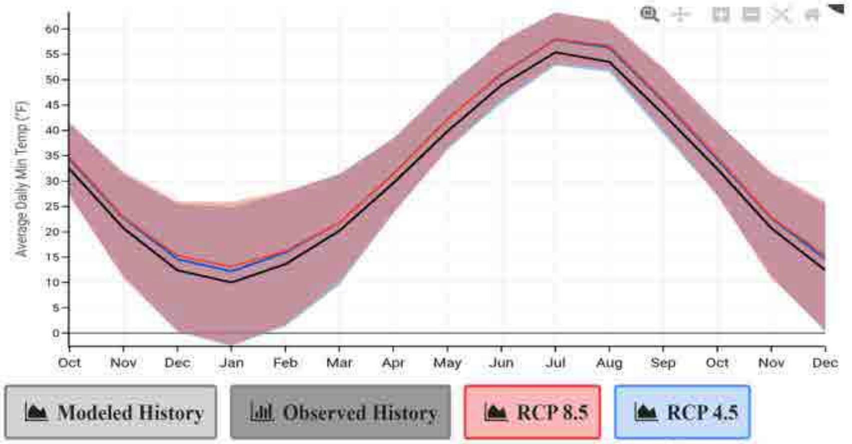
The historical variability of extreme events such as wind event, is large. This variability and the influence of regional and local process on these events result in an inability to project these events under climate change. Kossin et al. (2017) conclude that the types of changes that would support an increase in the frequency and intensity of severe thunderstorms (tornadoes, hail, winds) are projected in current climate models. However, confidence in the details of those projections is low.

Figure 2-6. Historical observations and future projections for monthly average maximum temperature, monthly minimum temperature, and total precipitation in the Limestone Plateau – Core Highlands ecoregion, under two future scenarios, RCP 4.5 and RCP 8.5. Historical observations reflect the 1961-1990 period, and projections are for the 2036-2060 period. Source: U.S. Government (2020)

A. Monthly mean maximum temperature (°F)



B. Average mean minimum temperature (°F)



C. Total precipitation

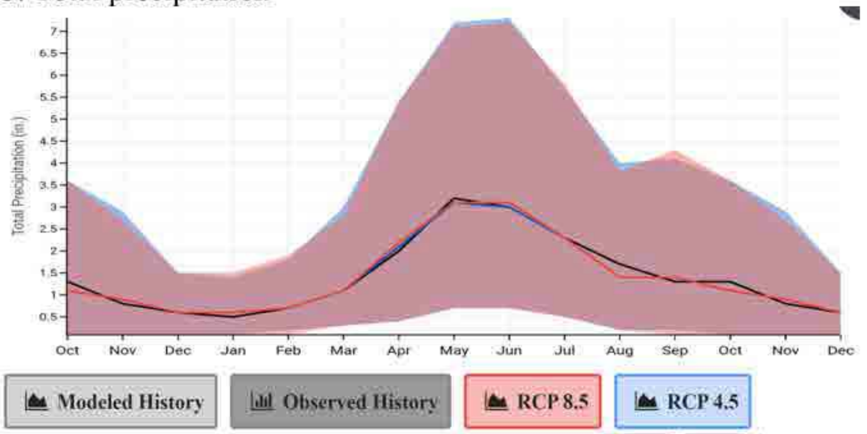
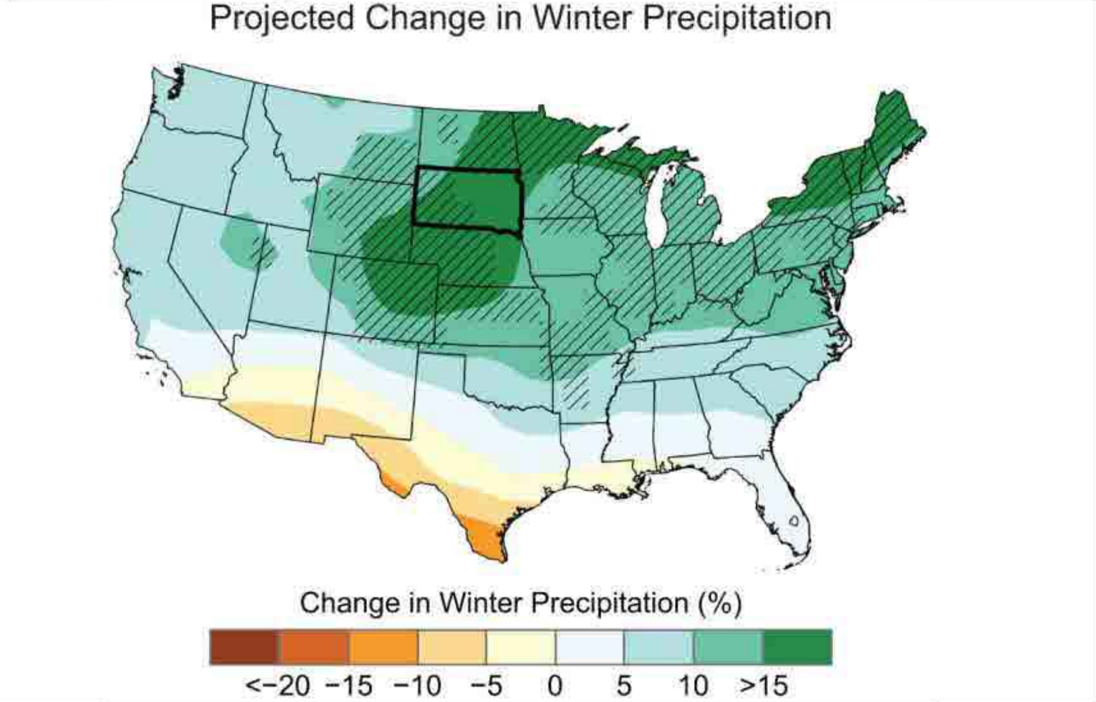


Figure 2-7. Projected changes in winter precipitation (%) for the middle of the 21st century compared to the late 20th century under RCP 8.5. Hatching represents areas where the majority of climate models indicate a statistically significant change. Winter precipitation is projected to increase by 10%–20%. South Dakota is part of a large area across the northern and central United States with projected increases in winter precipitation. Source: CICS-NC, NOAA NCEI, and NEMAC. (Frankson et al. 2017)



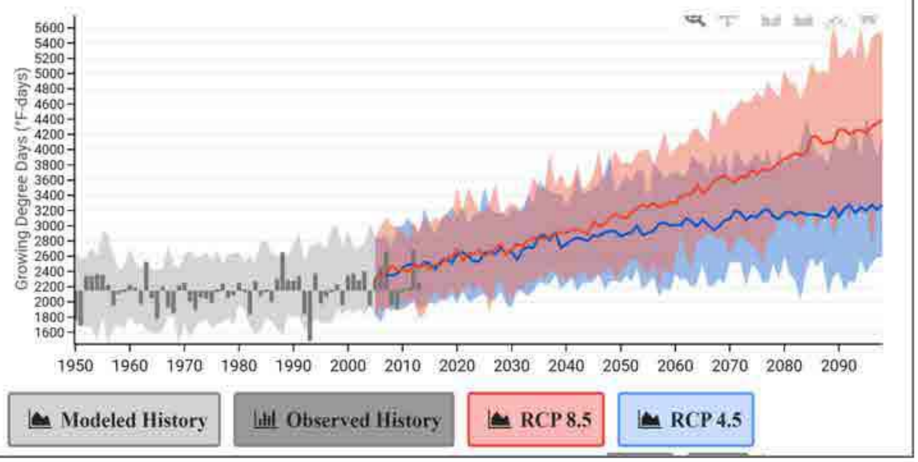
Growing Degree Days and Growing Season

The warming temperatures, particularly on the shoulder seasons, may affect the length of time plants can grow. We explore two ways to look at those changes. The first, growing degree days, focuses only on changes in temperature. This metric reflects the hours that plants and animals are able to grow and develop over the year – it is not limited by a set period of days or months. Over the 1950-2013 period, the mean annual growing degree days was 2149 degree days, ranging from a low in the year 1993 of 1485 growing degree days to a high in the year 2012 of 2690 days. Growing degree days are projected to increase through the 2036-2065 period, an average change of 792 degree days under RCP 4.5 to 1011.6 under RCP 8.5 (table 2-5, Figure 2-8). These projections suggest growing degree days increasing 36% under RCP 4.5.

Table 2-5. Projected change in growing degree days by the period 2036-2065 from the 1961-1990 baseline period under two scenarios (RCP 4.5 and RCP 8.5) for the Limestone Plateau – Core Highlands ecoregion. All changes are statistically significant at the 95% level. Source: U.S. Government (2020)

Black Hills Limestone Plateau and Core Highlands				
Variable	Scenario	Min	Mean	Max
Growing Degree Days				
	RCP 4.5	562.5	792	1017.6
	RCP 8.5	742.4	1011.6	1269.1

Figure 2-8. Projected changes in growing degree days for the Limestone Plateau- Core Highlands Ecoregion. Growing degree days is a measure related to the length of time conditions are right for plants and animals to grow or develop. As development can only occur when temperature exceeds a species' base temperature (50°F for these calculations), values are calculated by subtracting 50°F from the mean daily temperature and summing the positive results over the period of interest. Source: U.S. Government (2020)

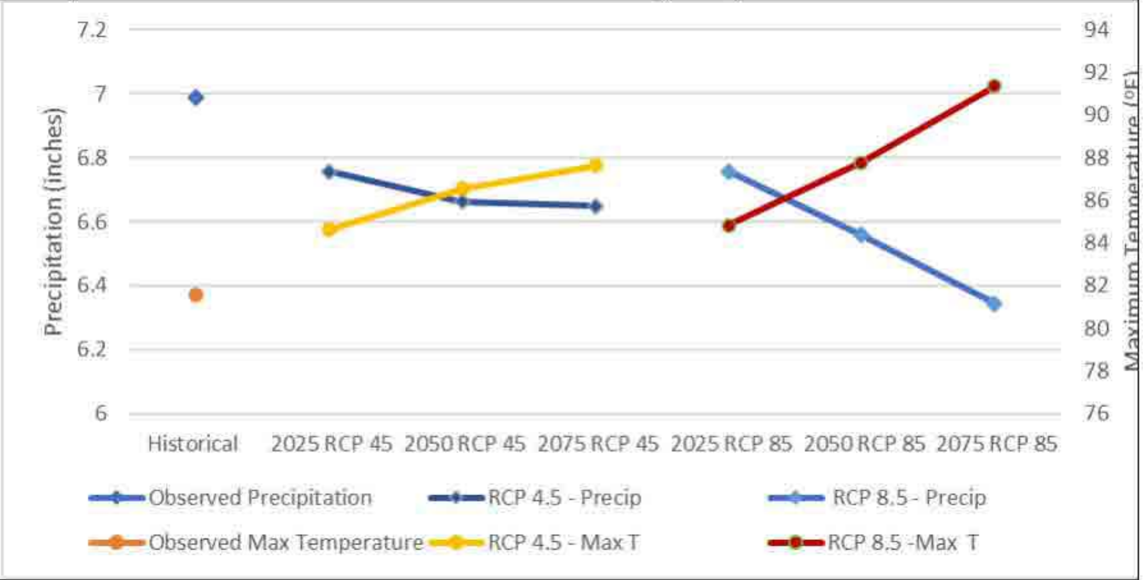


The length of the growing season, time between last frost in spring and first frost in fall, has implications for the productivity of forests. The growing season is short in the Black Hills. Depending upon the USDA zone, the last frost can occur between June 10 to June 20 or July 21 to July 31. First frosts in the fall for most of the Hills occur between September 10 and 20, although at high elevation, first frosts can occur between September 1 and 10.

Looking at the mean maximum temperature and total precipitation for the months of June through August, the projected precipitation declines slightly and mean maximum temperature for these three month increases over the projection periods under both RCP 4.5 and RCP 8.5 (Figure 2-9). Changes in precipitation have greater uncertainty than temperature. Given the larger changes in temperature, the growing season is likely to be drier in the future. The projections for

September might suggest that the growing season could extend into September, and the precipitation projections suggest a slight increase in September precipitation (Figure 2-6).

Figure 2-9. Historical observed (1961-1990) and projected mean maximum temperature (^{o}F) and total precipitation (inches) for growing season, defined as June through August under scenarios RCP 4.5 and RCP 8.5 for the Limestone Plateau – Core Highlands ecoregion. Three projection periods are shown: 2025, 2050, and 2075, where the mean is the 30-year period, e.g. for 2050, from 2036-2065. Source: U.S. Government (2020).



Conclusions

The Black Hills region is unique as a series of mountain ranges isolated from the nearest mountain ranges and rising above the surrounding Great Plains by as much as 3,500 feet. This contrast in elevation provides a wide contrast in temperature from the surrounding plains – higher elevations are cooler in the Black Hills which has ecological features similar to the Rocky Mountains (ponderosa pine, frequent fire regime). This elevational gradient also influences the formation of thunderstorms and the influence of cold winter-time Arctic fronts. The complex terrain of these isolated mountain ranges makes projecting climate at this fine scale a challenge. Perhaps more than other National Forests, the experiential knowledge of local land managers will be important in interpreting the likely future projections and consequences of temperature, precipitation, rainfall intensity, dry days, and changes in the growing season.

Maximum and minimum temperature are projected to rise over the next 50 years more than they have changed over the last 100 years. The average minimum temperature may be above freezing by mid-century, a potentially significant change in hydrology as well as growing season. Maximum temperatures will be hot, the number of days each year above 95^{o}F is likely to go from 7 days to 23 days a year – this is beyond any year in the historical record. While the northern Great Plains is projected to see increased precipitation, the projection for the Black Hills is positive but very small. Precipitation projections have more uncertainty than temperature projections, particularly as regional and local characteristics influence precipitation dynamics. It is likely that the Black Hills will see increased intensity and frequency of heavy rainfall events, which also have consequences to hydrology. It is also likely that the Black Hills will see compound extreme events, such as in 2012 when drought and hot temperatures coincided with many fires on the Black Hills NF. Drawing on past experiences such as 2012 may help plan for future extreme events. Scientific information in this chapter combined with the experiential knowledge of the Black Hills resource managers can inform planning, monitoring and management of natural resources and ecosystem service in the Black Hills National Forest.

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3. Hydrology and watersheds

Jessica Halofsky and Charlie Luce

Effects on water will be a major determinant of how climate change impacts ecosystems. In the Black Hills region, climate change will affect watersheds by:

- Reducing snowpack and the length of time snow persists;
- Increasing the intensity of rainstorms and the potential for flooding in spring and early summer;
- Increasing streamflow variability, with some high flow years and some low flow years;
- Affecting other disturbances processes, including wildfire and insect outbreaks, which affect runoff and potential for mass wasting.

These climate change effects on hydrology are discussed in more detail in the sections below.

Snowpack

Snowpack declines, particularly in spring, are among the most widely cited changes occurring with climate change (Brown and Robinson 2011, Gan et al. 2013, Easterling et al. 2017). In general, snowpack depth, extent, and duration are expected to decrease, particularly at lower and mid elevations, because of warmer temperatures and earlier melt (Luce et al. 2014, Kunkel et al. 2016, Musselman et al. 2021). The degree of change expected as a result of warming varies over the landscape as a function of current temperature (Luce et al. 2014, Ikeda et al. 2021). Places that are warm (near the melting point of snow) are expected to be more sensitive than places where temperatures remain subfreezing throughout much of the winter despite warming (Woods 2009).

Snow storage comprises both the amount of water stored in the snowpack and how long the snow lasts. The amount of water in the snowpack is represented as snow water equivalent (SWE) on April 1st, and duration is represented as snow residence time (SRT) (Luce et al. 2014). The SWE on April 1st is a widely used indicator of water availability for the coming spring runoff and irrigation season. The SRT is the average amount of time that any new snow will last.

April 1st SWE is projected to decrease across most of the Black Hills National Forest, ranging from a complete loss in the lower and mid-elevations to significant declines in SWE and SRT at higher elevations (Figures 3.1 and 3.2). Snow is already mostly absent or ephemeral in the southern and eastern portions of the forest at lower elevations, and in these locations, warming temperatures will change SWE or SRT little, because there is little snow to lose. For the upper elevations of the forest, average SRT is expected to decline by about 4–5 weeks relative to current SRT by 2080.

Changes in Precipitation and Flooding

Precipitation has a direct effect on hydrologic processes, but climate change projections for precipitation are more uncertain than those for temperature because of uncertainty in projecting changes in the large-scale circulation that affects the formation of clouds and precipitation (Shepherd 2014). For the Black Hills National Forest (Black Hills NF), the projected trend is an increase in precipitation, with significant increases in winter and spring (see climate section). Late summer precipitation may decrease. Overall, mean annual streamflow is projected to increase (Figure 3). Historically, the greatest amount of precipitation is received during May and June in the Black Hills (Driscoll et al. 2000). If precipitation increases during these months, as some models project, then runoff and flooding will likely increase.

Analyses of the last half of the 20th and early 21st century for the Missouri River watershed suggest that streamflows have increased in eastern part of the watershed, including the Black Hills (Norton et al. 2014). Similarly, an analysis for South Dakota for the last 30 years showed a significantly increasing streamflow trend, and a significant increase in one-day maximum streamflow, at a gauging station in the Black Hills (Kibria et al. 2016). These trends may be due to increasing precipitation in the region, particularly in fall and winter (Kibria et al. 2016), or as a result of increasing runoff efficiency because more water is being focused into larger individual events (e.g. Dai et al 2020). Historical analyses based on weather stations do not indicate clear trends in total annual precipitation (see climate section).

The Variable Infiltration Capacity hydrologic model (driven by five different global climate models) was used to project future flood risk for the Black Hills NF. The model projections suggest that 1.5-year flood magnitude is likely to increase across the forest (Figure 4). However, larger 10-year (Figure 3-5) and 25-year (Figure 3-6) floods are projected to increase in magnitude in only some streams. With loss of snow and potentially increased precipitation, winter flows are projected to increase, and winter floods that exceed the 95th percentile of flows are projected to increase by 25–50% across the forest (Figure 3-7).

Precipitation intensity also affects flood risk. One key outcome of a warming atmosphere is that when precipitation occurs, the same total volume is expected to fall with greater intensity, leading to shorter events and longer dry periods between events (e.g., Dai et al. 2020). There is high confidence that the number of heavy precipitation events (events with greater than 1 inch per day of rainfall) will increase across the contiguous United States in the future (Easterling et al. 2017, Frankson et al. 2017). These heavy precipitation events may contribute to increased flooding (Wehner et al. 2017), particularly if they occur in the late spring and early summer when flows are already high in the Black Hills. Flood events can threaten infrastructure, such as roads, recreation sites, and water management facilities (e.g., diversions, dams) (see roads section).

Changes in Low Flows

Despite projections of increased annual flows in the Black Hills (Figure 3-3), summer low flows may decline in some years (e.g., Figure 3-8). The primary mechanism expected to drive lower summer flows is reduced snowpack in winter (Figures 3-1 and 3-2), leading to earlier runoff (Figure 3-9) and less stored water to sustain summer flows. However, the VIC simulations do not include the effects of large groundwater reserves, such as those found in the limestone plateau portions of the Black Hills, and thus this effect could be moderated in parts of the region where groundwater flow contributes a substantial volume of water to late summer flows (areas outside of the "crystalline core" as described in Stamm et al. 2015).

Overall, the interannual variation in climate in the Black Hills region is high and increasing, and this year-to-year variation could overshadow the projected changes in mean streamflow (Conant et al. 2018), leading to both wetter and drier extremes. There was major flooding in the Upper Missouri River Basin in 2011, followed by a severe drought in 2012, and this type of variability is likely to become more common with climate change (Conant et al. 2018). Shifts between overabundant and scarce water resources will pose significant challenges for water management and biota.

Wildfire effects on hydrology and aquatic habitat

A warmer climate with more frequent and severe droughts and lower snowpack is expected to increase the frequency and magnitude of wildfire, which will in turn affect hydrologic and geomorphic responses in watersheds (e.g., Goode et al. 2021). The effects of wildfire on hydrologic systems and associated terrestrial effects (e.g., erosion) are often local (e.g., within a small watershed). However, they can also be cumulative, where very large or multiple fires have occurred in contiguous watersheds over a relatively short time (a few decades) (Luce et al. 2012). Fire effects also often occur through multiple pathways, such as the combined effects of fire (short-term), timber harvest (mid-term), and climate change (long-term) on water yield or flooding. Peak flow in streams may be over 200 times higher post-fire than pre-fire (especially where soils are hydrophobic), although it is more commonly less than 10 times that of peak flow before fire (Shakesby and Doerr 2006).

More subtle changes also occur following fire, including altered snowmelt, water yield, and low flows (Luce et al. 2012). Annual water yields may increase following fire (Shakesby and Doerr 2006), because less water is used by vegetation (Andréassian 2004, Brown et al. 2005). In general, water yield increases more in wet locations and in wet years than in drier locations and dry years, though not always (Adams et al. 2012, Goeking and Tarbton 2020), and increased annual water yield generally enhances late-season streamflows (Luce et al. 2012).

Hillslope and steep-channel processes, such as surface erosion and mass wasting, are often prominent after wildfire (Cannon et al. 2001, Miller et al. 2003, Moody and Martin 2009, Pierce et al. 2004), affecting natural resources, property, and sometimes human safety. Loss of vegetative cover combined with alteration of soil properties increase the potential for surface erosion and mass wasting. Loss of trees reduces interception of raindrops by tree crowns and reduces root strength in the soil. Loss of trees, shrubs, grass, and surface organic layers expose the soil surface, allowing it to be splashed and washed away more readily, increasing downhill transport of soil particles (Istanbulluoglu et al. 2003).

Initiation of debris flows after wildfires is of particular concern in steep terrain where geomorphic disturbance is more likely when vegetation is removed. Numerous studies have documented increased frequency of debris flows following large, severe fires (Gabet and Bookter 2008, Istanbulluoglu et al. 2002, Pierce et al. 2004, Rengers et al. 2016). Effects of debris flows can be transmitted through some landscapes and riverscapes for long periods (May and Gresswell 2003).

Mass wasting events, such as debris flows, can result in local fish population extirpations (Rieman and Dunham 2000, Dunham et al. 2003). However, these events also provide large amounts of gravel, cobbles, and logs that contribute to habitat complexity and quality of streams over the long term (Benda et al. 2003, Penaluna et al. 2018), and species can recolonize over time. Interactions between geomorphic disturbances and stream habitat are complex and variable over space and time, with biological effects depending on the organism and post-disturbance environment, including biotic and climatic components (Rieman et al. 2012, Neville et al. 2012, Rosenberger et al. 2012, Young 2012).

Estimated increases in stream temperature following wildfire range from a mean of 0.9 to 7.2 °F and a maximum of 4.5 to 18.0 °F (Dunham et al. 2007, Isaak et al. 2010). Increases depend on stream size, orientation, surrounding landforms, and canopy removal, and the effects of a combination of fire and debris flow can be much greater than fire alone. In a study of small streams in the Boise River basin where wildfire had occurred, the maximum daily temperature of burned streams was 6.1 °F warmer than unburned streams, and streams that had experienced both fire and passage of a debris flow were 14.2 °C warmer (Dunham et al. 2007). Increased radiation accounted for 50 percent of the warming (Isaak et al. 2010).

The long-term effects of fire and climate on stream systems will be affected by riparian vegetation (Dwire and Kauffman 2003). Riparian vegetation contributes significantly to the maintenance of aquatic habitat, providing (1) shade for thermal modification of stream temperature, (2) inputs of large wood for instream habitat complexity, (3) allochthonous organic matter inputs to aquatic food webs, and (4) streamside habitat and stabilization of streambanks (Dwire and Kauffman 2003, Luce et al. 2012). Upland and riparian vegetation moderate incoming radiation to streams following fire, and recovery of vegetation after fire may require as little as a few years or up to a few decades, depending on the degree of channel disturbance (Dunham et al. 2007). With increasing air temperature, riparian microclimates may warm, and coniferous streamside vegetation may become more similar to upland vegetation. During wildfires, these riparian areas may increasingly burn like surrounding uplands (Dillon et al. 2011, Luce et al. 2012), leading to increased incoming radiation to streams over longer periods of time.

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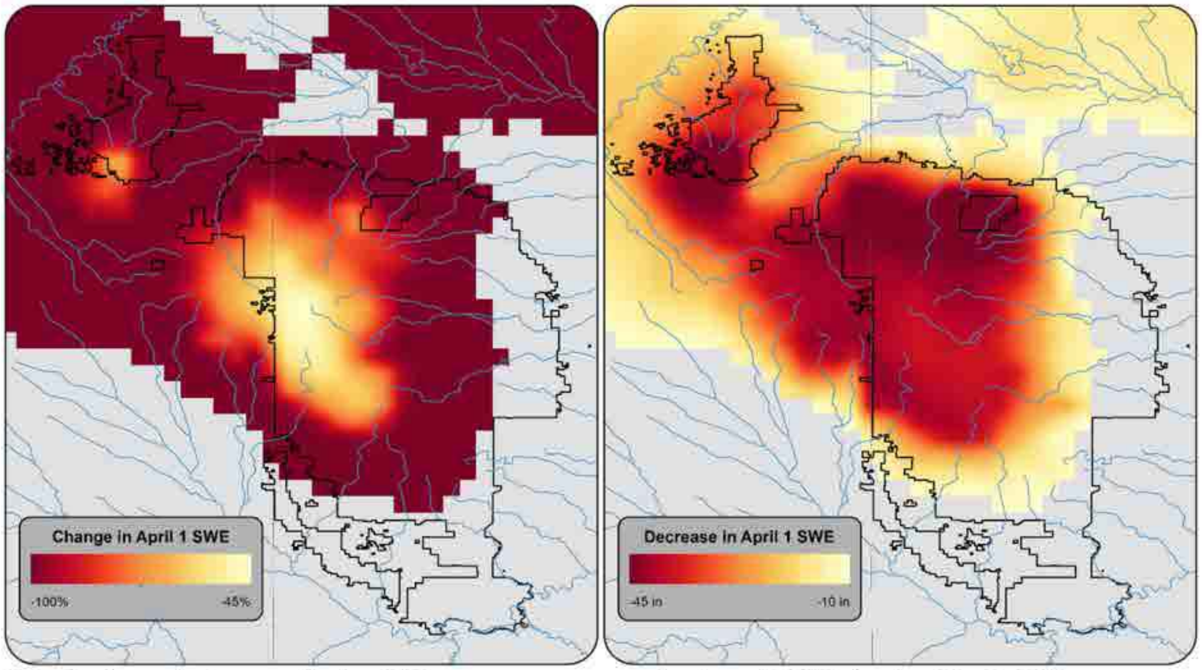


Figure 3-1. Projected changes in April 1st snow-water equivalent (SWE) in the Black Hills National Forest region from historical conditions (1975–2005) to the 2080's (2071–2090) based on temperature increases projected from a 20 global climate model ensemble mean under RCP 8.5. Data and methods description are available at the National Forest Climate Change Maps webpage. Figure by R. Norheim.

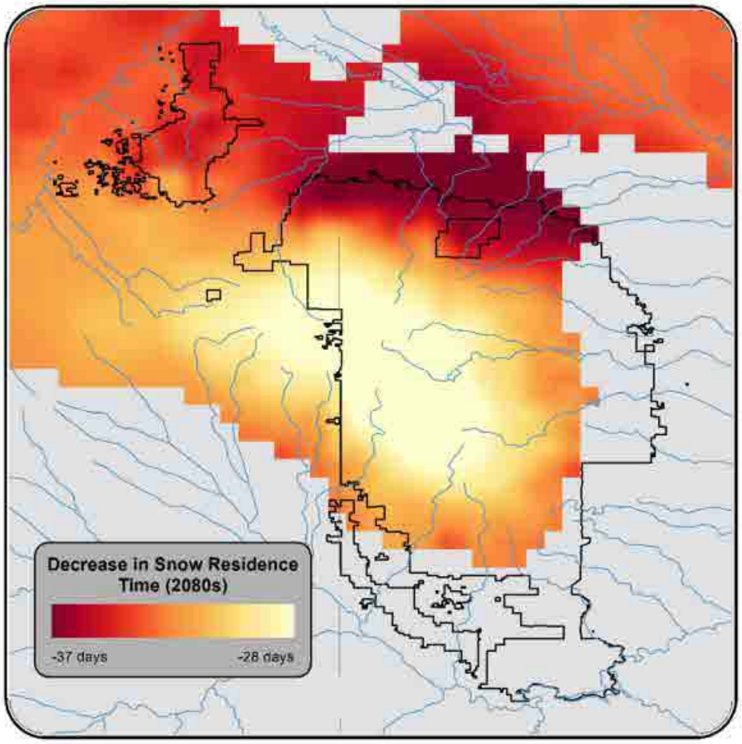
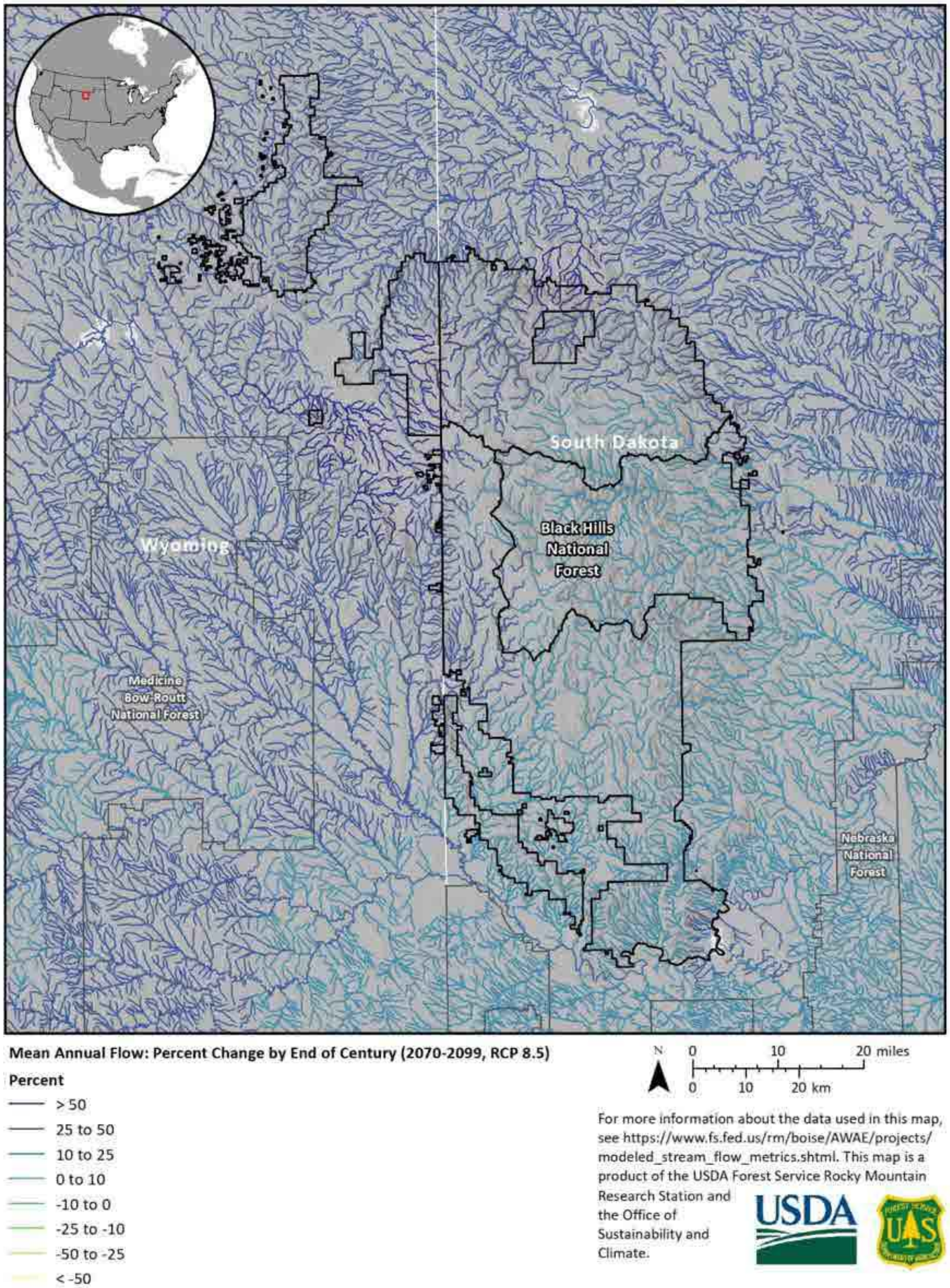


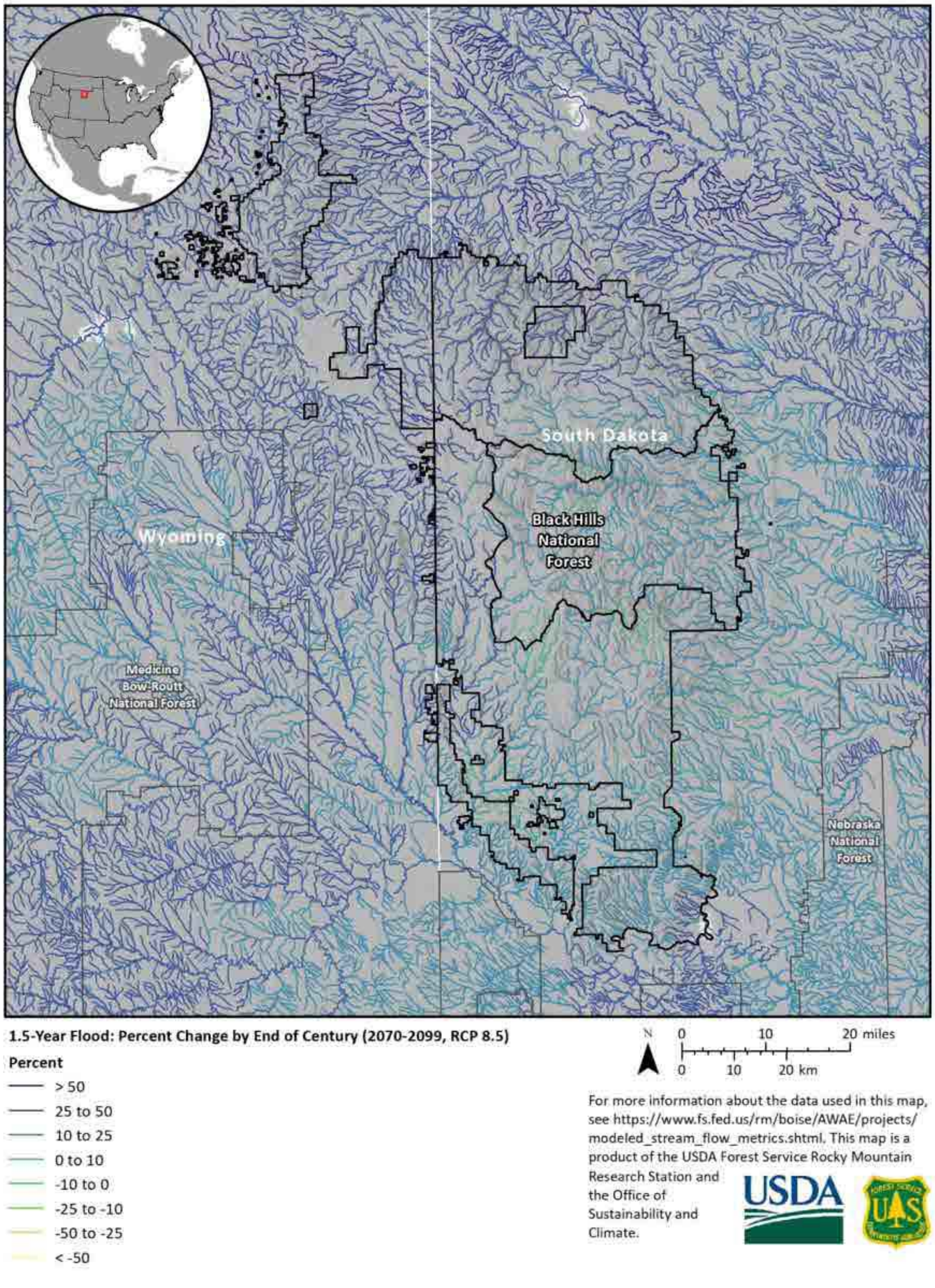
Figure 3-2. Projected changes in snow residence time (SRT) in the Black Hills National Forest region from historical conditions (1975–2005) to the 2080's (2071–2090) based on temperature increases projected from a 20 global climate model ensemble mean under RCP 8.5. Data and methods description are available at the National Forest Climate Change Maps webpage. Figure by R. Norheim.



Mean Annual Flow: Percent Change by End of Century (2070-2099, RCP 8.5)

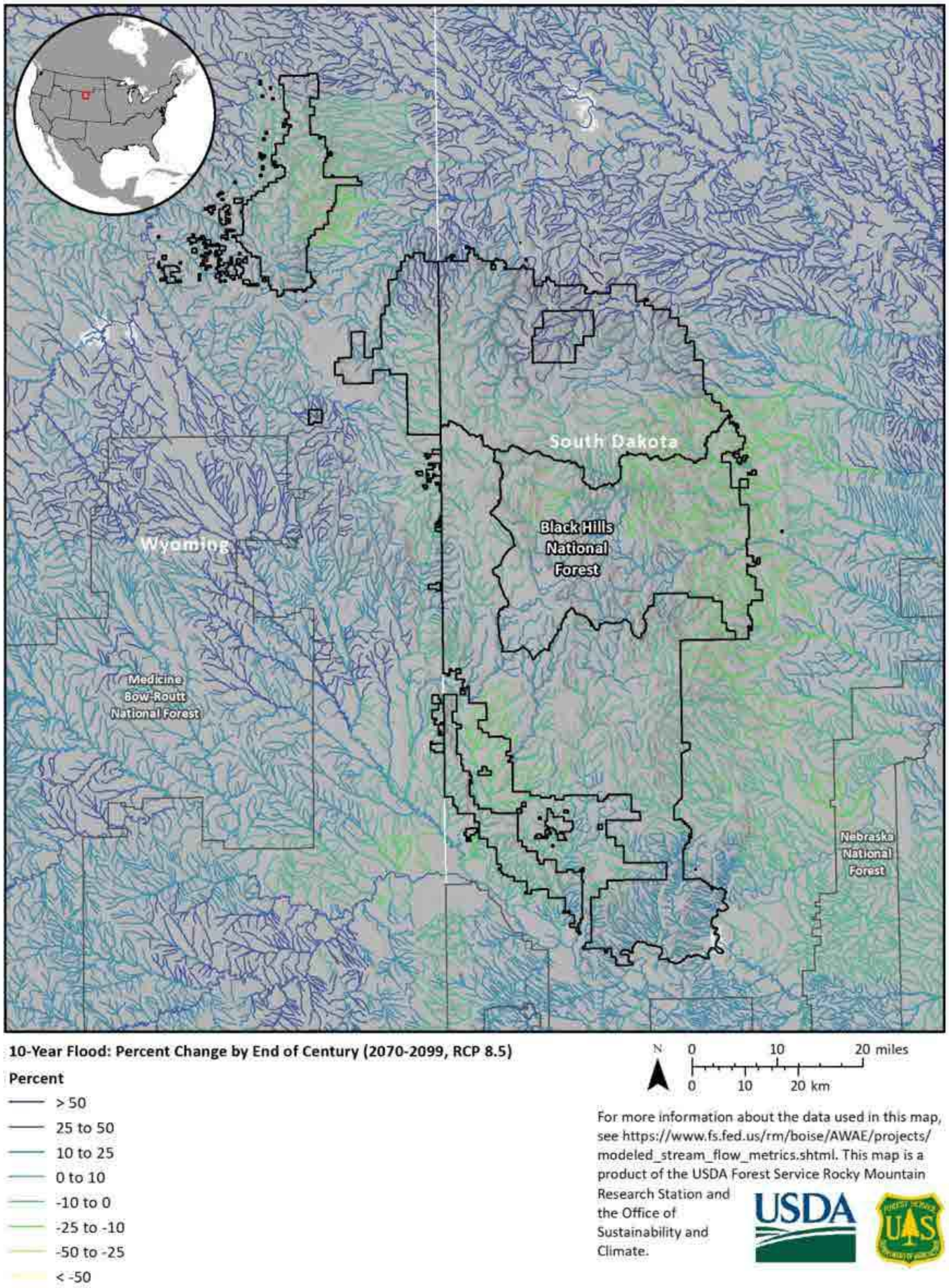
For more information about the data used in this map, see https://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml. This map is a product of the USDA Forest Service Rocky Mountain Research Station and the Office of Sustainability and Climate.

Figure 3-3. Projected percent change in mean annual flow between a historical period (1970–1999) and the 2080s under the Representative Concentration Pathway 8.5 greenhouse gas scenario, based on Variable Infiltration Capacity (VIC) hydrologic modeling.



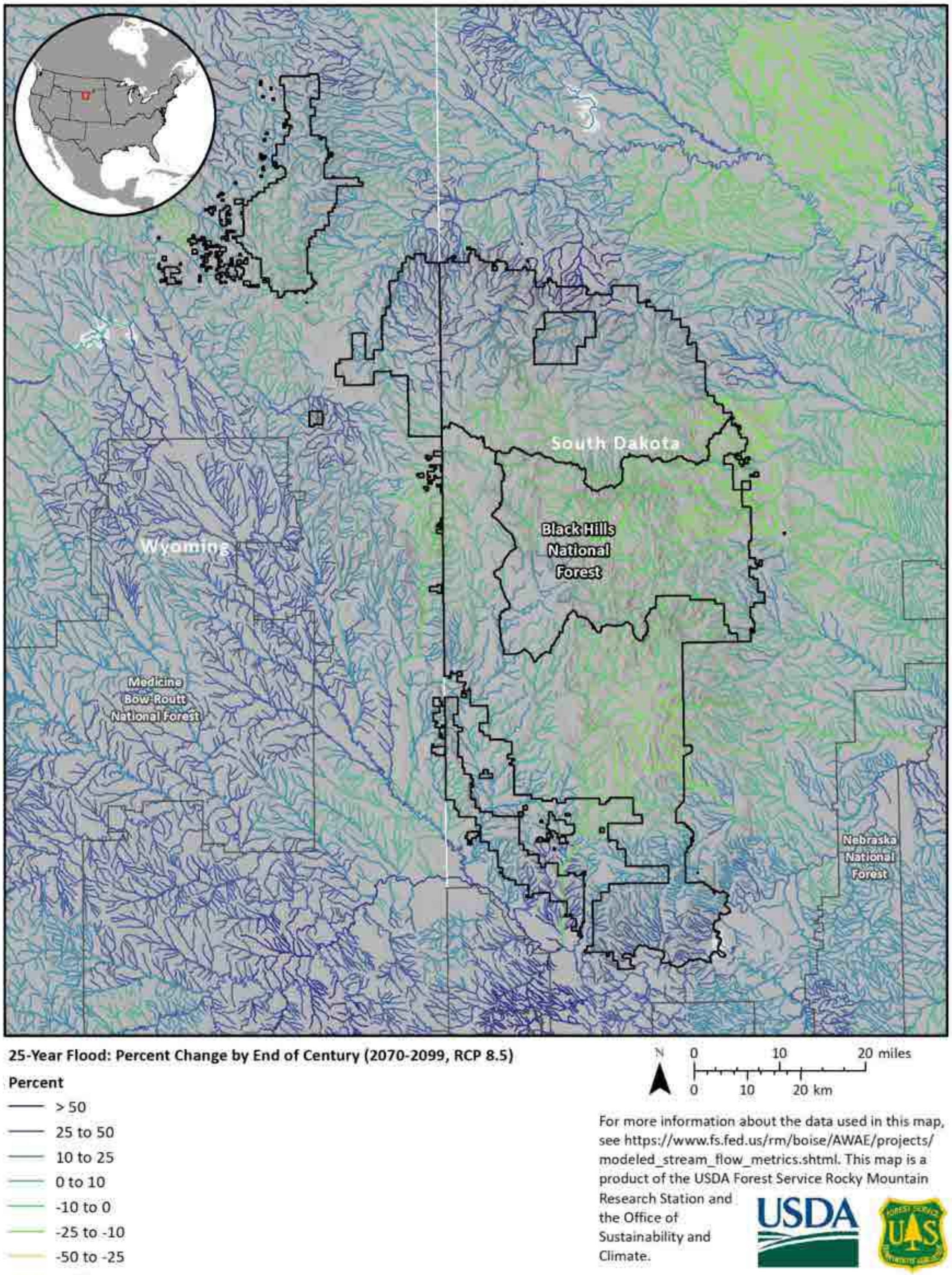
For more information about the data used in this map, see https://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml. This map is a product of the USDA Forest Service Rocky Mountain Research Station and the Office of Sustainability and Climate.

Figure 3-4. Projected percent change in 1.5-year floods (bankfull flow) between a historical period (1970–1999) and the 2080s under the Representative Concentration Pathway 8.5 greenhouse gas scenario, based on Variable Infiltration Capacity (VIC) hydrologic modeling.



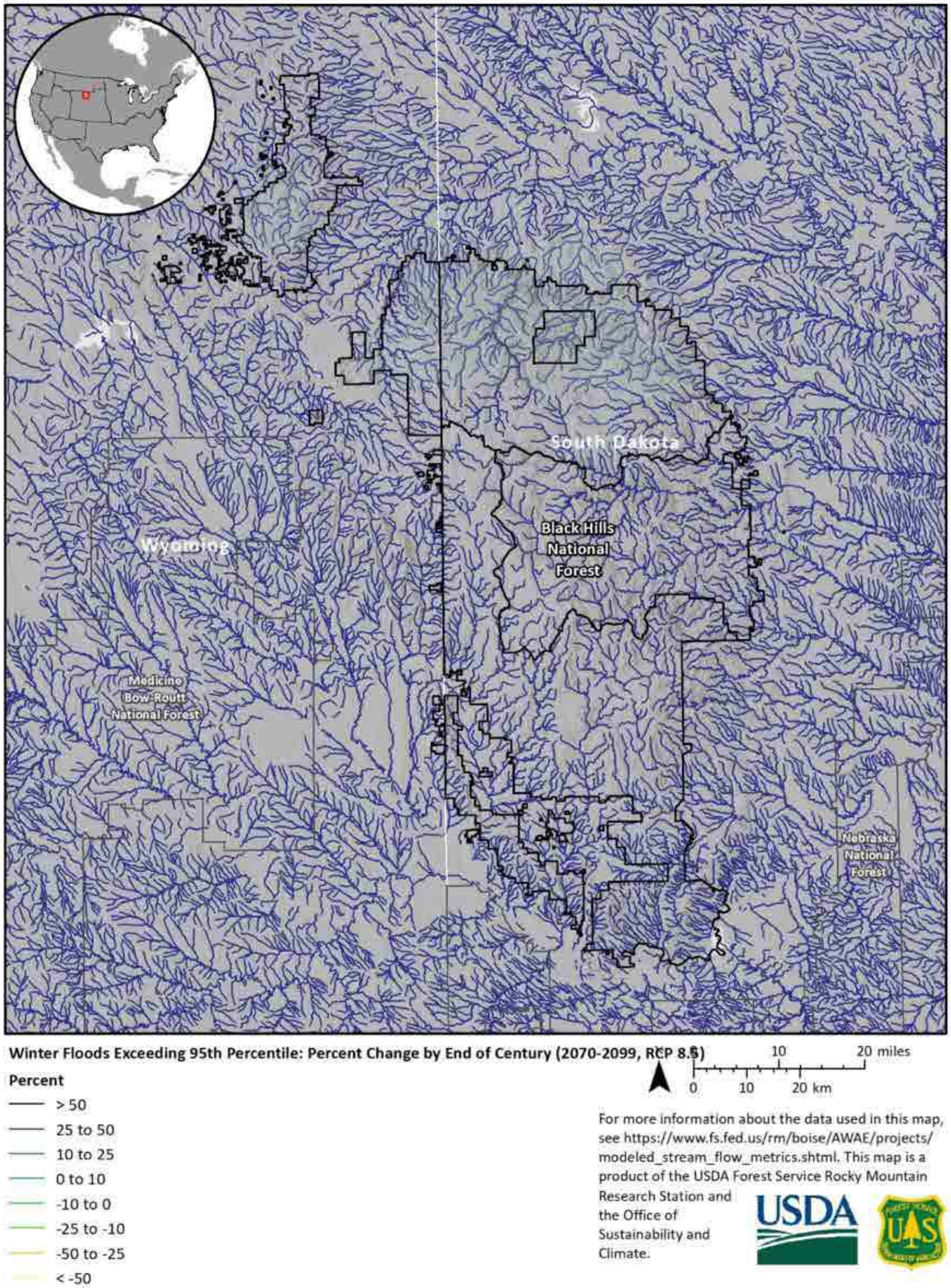
For more information about the data used in this map, see https://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml. This map is a product of the USDA Forest Service Rocky Mountain Research Station and the Office of Sustainability and Climate.

Figure 3-5. Projected percent change in 10-year floods between a historical period (1970–1999) and the 2080s under the Representative Concentration Pathway 8.5 greenhouse gas scenario, based on Variable Infiltration Capacity (VIC) hydrologic modeling.



For more information about the data used in this map, see https://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml. This map is a product of the USDA Forest Service Rocky Mountain Research Station and the Office of Sustainability and Climate.

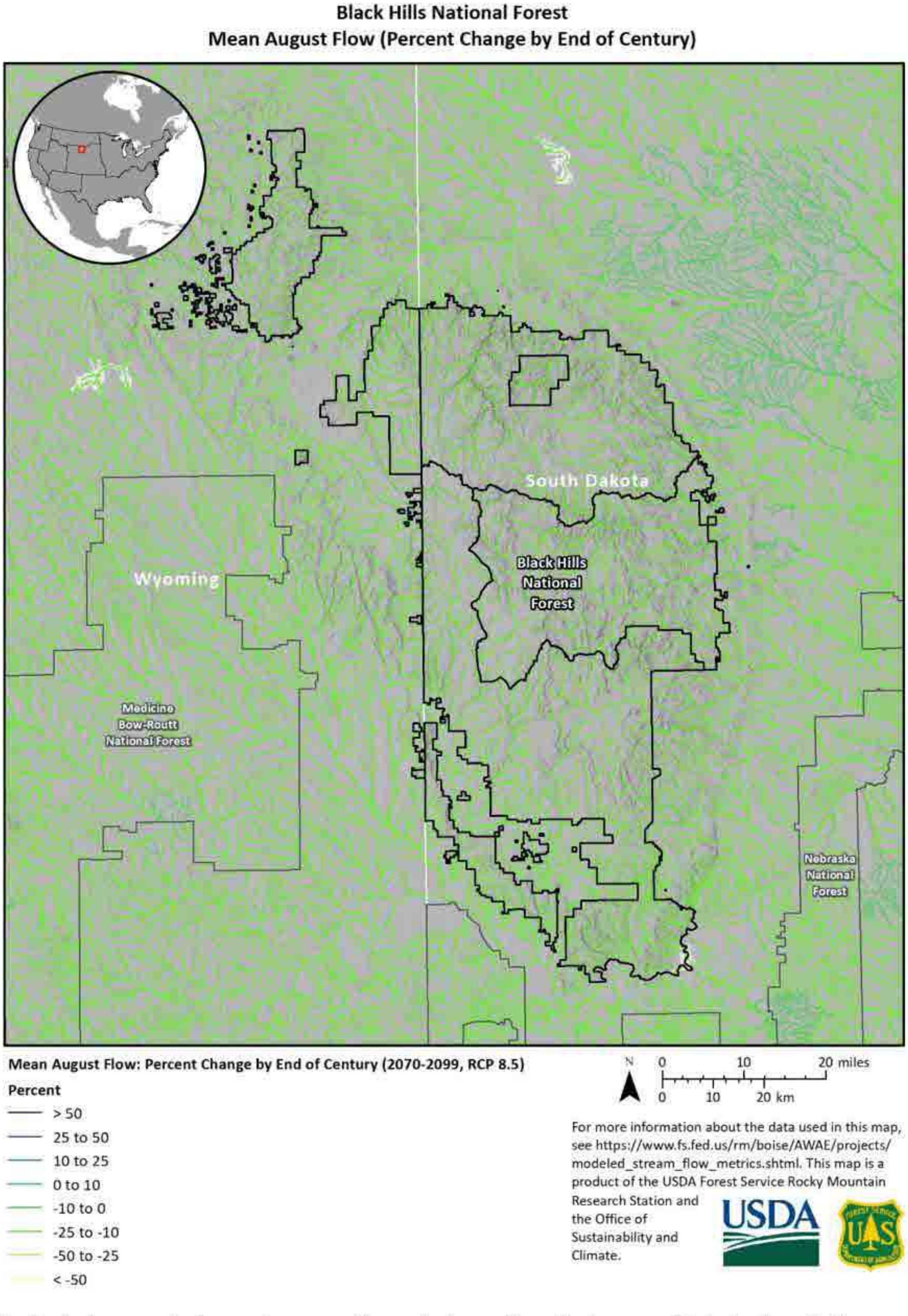
Figure 3-6. Projected percent change in 25-year floods between a historical period (1970–1999) and the 2080s under the Representative Concentration Pathway 8.5 greenhouse gas scenario, based on Variable Infiltration Capacity (VIC) hydrologic modeling.



Winter Floods Exceeding 95th Percentile: Percent Change by End of Century (2070-2099, RCP 8.5)

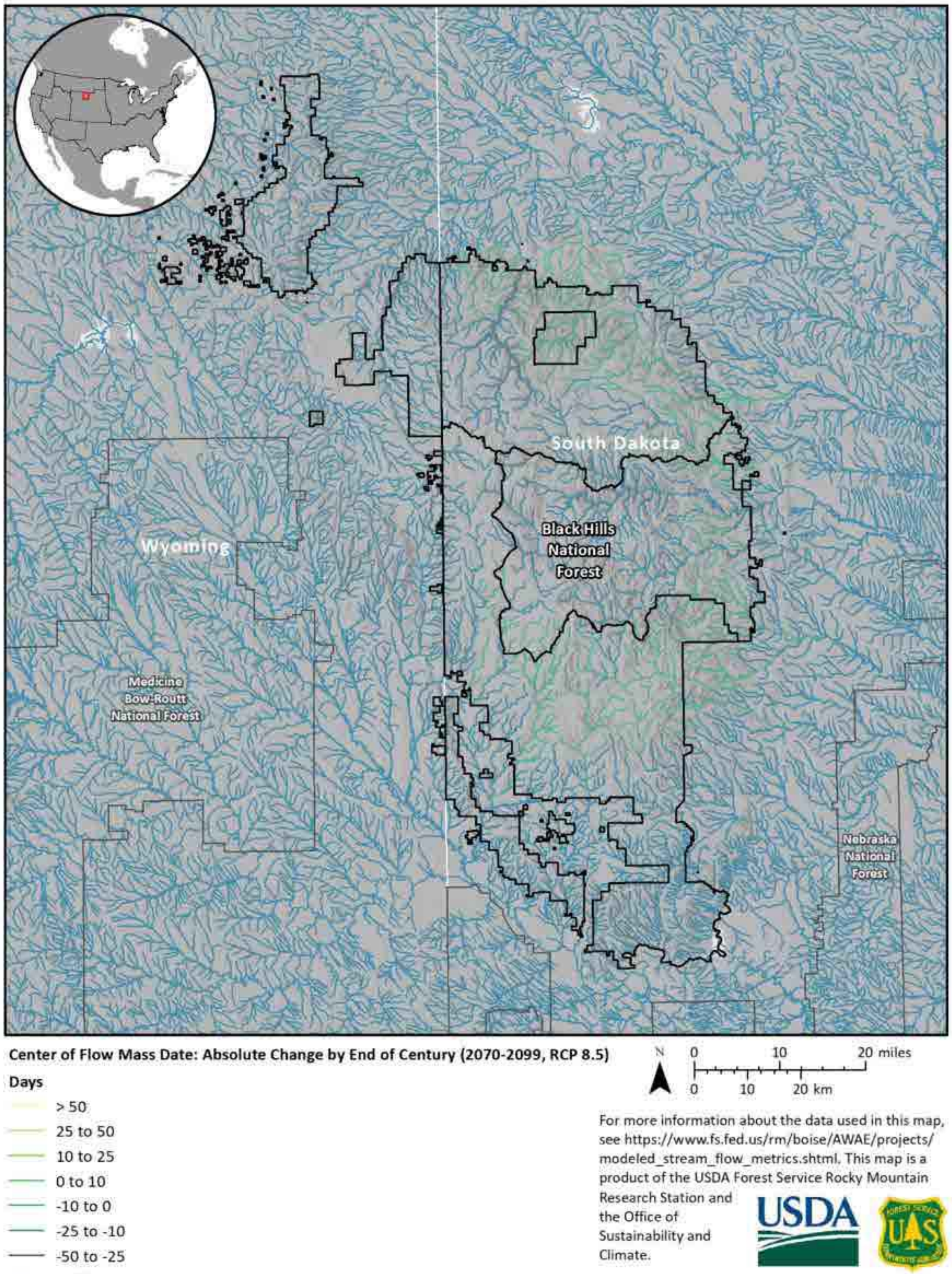
For more information about the data used in this map, see https://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml. This map is a product of the USDA Forest Service Rocky Mountain Research Station and the Office of Sustainability and Climate.

Figure 3-7. Projected percent change in number of winter floods that exceed the 95th percentile of flows between a historical period (1970–1999) and the 2080s under the Representative Concentration Pathway 8.5 greenhouse gas scenario, based on Variable Infiltration Capacity (VIC) hydrologic modeling.



For more information about the data used in this map, see https://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml. This map is a product of the USDA Forest Service Rocky Mountain Research Station and the Office of Sustainability and Climate.

Figure 3-8. Projected percent change in mean August streamflow between a historical period (1970–1999) and the 2080s under the Representative Concentration Pathway 8.5 greenhouse gas scenario, based on Variable Infiltration Capacity (VIC) hydrologic modeling.



For more information about the data used in this map, see https://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml. This map is a product of the USDA Forest Service Rocky Mountain Research Station and the Office of Sustainability and Climate.

Figure 3-9. Projected percent change in center of flow mass date (when the highest flows occur) between a historical period (1970–1999) and the 2080s under the Representative Concentration Pathway 8.5 greenhouse gas scenario, based on Variable Infiltration Capacity (VIC) hydrologic modeling.

4. Fish

Jessica Halofsky and Dan Isaak

Climate change is expected to alter aquatic habitats in the Black Hills in the 21st century. Direct changes are likely to include warmer water temperatures, earlier snowmelt-driven runoff (Figure 3-9), increased flooding (Figures 3-7), and more variable summer streamflows (Figure 3-8)[1], as well as indirect changes caused by shifts in disturbance regimes (described in Chapter 3). For fish and many other aquatic species, changes in habitat and hydrology are likely to lead to shifts in their abundance and distribution because many of these species are ectothermic (cold blooded). Thus, environmental conditions determine their metabolic rates and nearly every aspect of their life stages, including growth rate, migration patterns, reproduction, and mortality (Magnuson et al. 1979).

There is little long-term stream temperature monitoring in the Black Hills region to determine trends, and the Black Hills have a unique karst geology, which makes future stream temperature projections (such as those from the NorWeST model) uncertain. However, stream temperature is likely to increase with air temperature trends, albeit at a slower rate (Isaak et al. 2018). Temperature increases are likely to be greatest in areas without substantial groundwater influence.

In addition to temperature, species abundance and distribution can be influenced by competition with, or predation by, other fish. Three species of introduced salmonids (brook trout [*Salvelinus fontinalis*], brown trout [*Salmo trutta*], and rainbow trout [*Oncorhynchus mykiss*]) now constitute the majority of fish biomass in many streams in the Black Hills (Schultz et al. 2012). However, native species and non-native trout may, in some cases, have non-overlapping distributions (Schultz and Bertrand 2011).

Climate and nonnative species play a crucial role in aquatic ecology, but the relative importance of climatic factors is different for different species, and even different populations of the same species (Mantua et al. 2011). Below, we describe potential climate change effects on four species of interest for the Black Hills National Forest (Black Hills NF), including lake chub (*Couesius plumbeus*), mountain sucker (*Pantosteus jordani*), finescale dace (*Chrosomus neogaeus*), and longnose sucker (*Catostomus catostomus*), which are the species of greatest conservation concern in the region (SDGFP 2014). Their distribution on the forest is shown in Figure 4-1 based on data from a SDGFP database.

Lake chub

Lake chub are widely distributed across Canada and the northern portions of the U.S. The small populations in the Black Hills are disjunct and isolated from other populations (as a result of the last glaciation) at the southern extent of the species range. Historical accounts suggest that lake chub were widely distributed across the Black Hills, but more contemporary assessments indicate that distribution and populations have been significantly reduced (Isaak et al. 2003).

Lake chub can occur in both streams and lakes where they prefer clear, cool water with clean cobble or gravel substrates (Patton 1997). Lake chubs are spring spawners and usually breed in streams (Scott and Crossman 1973). Overall, the ecology of lake chub is not well

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[1] These figures are provided in the previous chapter.

understood, making it difficult to determine the potential effects of climate change on the species in the Black Hills.

Because of their limited distribution in the Black Hills region, extreme events, such as floods or droughts, could have major impacts on existing populations of lake chub, because there are no nearby populations to recolonize and provide resilience (Isaak et al. 2003). Large wildfires followed by storms could increase sedimentation and decrease water quality in reservoirs and streams, resulting in lake chub mortality. Increased stream, reservoir, and lake temperatures could similarly decrease habitat quality and have a negative effect on populations. Introduction and spread of predator species may cause additional mortality to lake chub and negatively affect populations of the species, but the degree to which Black Hills populations are currently affected by this mechanism is not well understood.

Mountain sucker

The Black Hills are the eastern extent of the distribution of the mountain sucker, which is distributed across western North America (Belica and Nibbelink 2006). Most populations of mountain sucker occur in the northern portion of the Black Hills (Figure 3-10), with the highest abundance in Whitewood Creek (Fopma 2020). A recent analysis suggested that established populations of mountain sucker in the Black Hills have remained relatively stable over the past 25 years (Fopma 2020). However, local population declines or extirpations and a range reduction in the southern portion of the Black Hills have been reported (Isaak et al. 2003, Schultz and Bertrand 2011).

Distribution models for the Black Hills NF (based on sampling conducted from 1988 to 2004) indicated that mountain suckers are more likely to be present in perennial streams, and those that are larger and steeper at higher elevations, or that are smaller and less steep at lower elevations (Dauwalter and Rahel 2008). Brook trout may exclude mountain suckers from cold, small headwater streams, but as water temperature and stream size increase, longnose dace, brown trout, and mountain sucker become more abundant in many downstream areas (Schultz et al. 2012). Mountain suckers are typically found in cool, clear waters (Dauwalter and Rahel 2008) and are positively associated with increased periphyton coverage that serves as an important food source (Schultz et al. 2016).

Perennial streams are critical to the mountain sucker (Dauwalter and Rahel 2008), and any enhanced flow variability from climate change that results in stream intermittency would likely have a negative effect on mountain sucker populations. Although mountain sucker do not currently appear to be limited by warm water temperature in the Black Hills, their probability of occurrence is highest where August mean stream temperatures are between 15 and 24 °C, so increased future temperatures beyond this range could lead to declines in abundance and range contractions (Schultz and Bertrand 2011). The distribution of the species may have to shift to cooler upstream areas, and extirpations may occur if suitable habitats do not exist upstream or if they are not accessible (Isaak et al. 2003). Stream turbidity may also increase after wildfire events, which are likely to occur more frequently with climate change. Increased sedimentation after fire could reduce periphyton food resources, or cause direct fish mortalities due to decreased water quality or the smothering of fish eggs (Isaak et al. 2003).

The Black Hills NF has reported the loss of mountain sucker populations where brown trout fisheries are maintained (USDA Forest Service 2006), and several analyses have found a negative effect of brown trout on mountain suckers (Dauwalter and Rahel 2008, Schultz et al. 2016). However, mountain sucker is less susceptible to elevated water temperatures and climate change than introduced salmonids, including brown trout (Schultz and Bertrand 2011). Thus, the negative effects of brown trout on mountain sucker populations may not be exacerbated by climate change. However, removal of brown trout where the two species overlap is likely to be important for any restoration efforts designed to expand the distribution of mountain sucker (Schultz et al. 2016, Fopma 2020).

Finescale dace

Finescale dace occurs in the Great Plains in isolated populations at the southern edge of their range in Wyoming, South Dakota, and Nebraska (Lee et al. 1980). They are primarily found in cool-water locations in the region, including low-gradient headwater streams, spring-fed lakes, and groundwater seeps (Isaak et al. 2003, Booher and Walters 2020). Finescale dace are primarily found in low abundance and in spatially disjunct populations in the Great Plains (Hoagstrom & Berry 2006). A 2003 conservation assessment indicated population declines of finescale dace in the Black Hills NF (Isaak et al. 2003), but there have since been introductions of the species in other parts of the forest (Booher and Walters 2020). Finescale dace are a state endangered species in South Dakota.

A recent study suggests that August water temperature is an important determinant of finescale dace occurrence across the Belle Fourche River basin and Niobrara River basin (south of the Black Hills in Wyoming and Nebraska), suggesting that summer thermal habitat is a limiting factor for these populations (Booher and Walters 2020). The study indicated a similar thermal optima of 15–20 °C in both the Belle Fourche River and Niobrara River basins, so increases in stream temperature with climate change may restrict finescale dace distribution in the Black Hills region (Booher and Walters 2020). However, in groundwater-influenced habitats where finescale dace are currently found, warming rates may be slower (Jyväsjärvi et al. 2015).

Severe droughts, which could increase with climate change may dry some finescale dace habitats and lead to population declines (Isaak et al. 2003). At the other extreme, larger or more frequent floods could damage lentic habitats associated with manmade or beaver dams where some finescale dace populations occur (e.g., Geis and Hemler reservoirs) and result in local population declines or extirpations (Isaak et al. 2003). Floods in the spring when spawning occurs could also destroy eggs, which are laid in clusters under logs and brush. Finescale dace are often found in ponds created by beaver dams, and thus any management actions to promote or reintroduce beaver would likely have a positive effect on finescale dace populations. Non-native species, including smallmouth bass (*Micropterus dolomieu*) and the introduced trouts, may negatively affect finescale dace in the Black Hills region (Booher and Walters 2020). However, further research is needed on the effects of non-native species on finescale dace in the region.

Longnose sucker

The longnose sucker is the most widely distributed sucker in North America, ranging throughout Canada, Alaska, the Great Lakes region, the upper Missouri River system, and extending into eastern Siberia. However, distribution on the Black Hills NF was historically, and is currently, very limited (Schultz et al. 2012). Longnose sucker is listed as a state threatened species for South Dakota, and its distribution in South Dakota is limited to tributary streams from the Cheyenne and Belle Fourche Rivers (SDGFP 2014). On the Black Hills NF, longnose sucker populations were reported to have declined between the 1950s and late 1990s.

Longnose suckers are found in clear, cool, spring-fed lakes and streams (SDGFP 2014). They are sensitive to increases in water temperature and decreases in water quality. Longnose suckers in the Black Hills are considered highly vulnerable to climate change because of their need for a specific habitat type, sensitivity to water temperature increases, and limited ability for dispersal and recolonization (SDGFP 2014).

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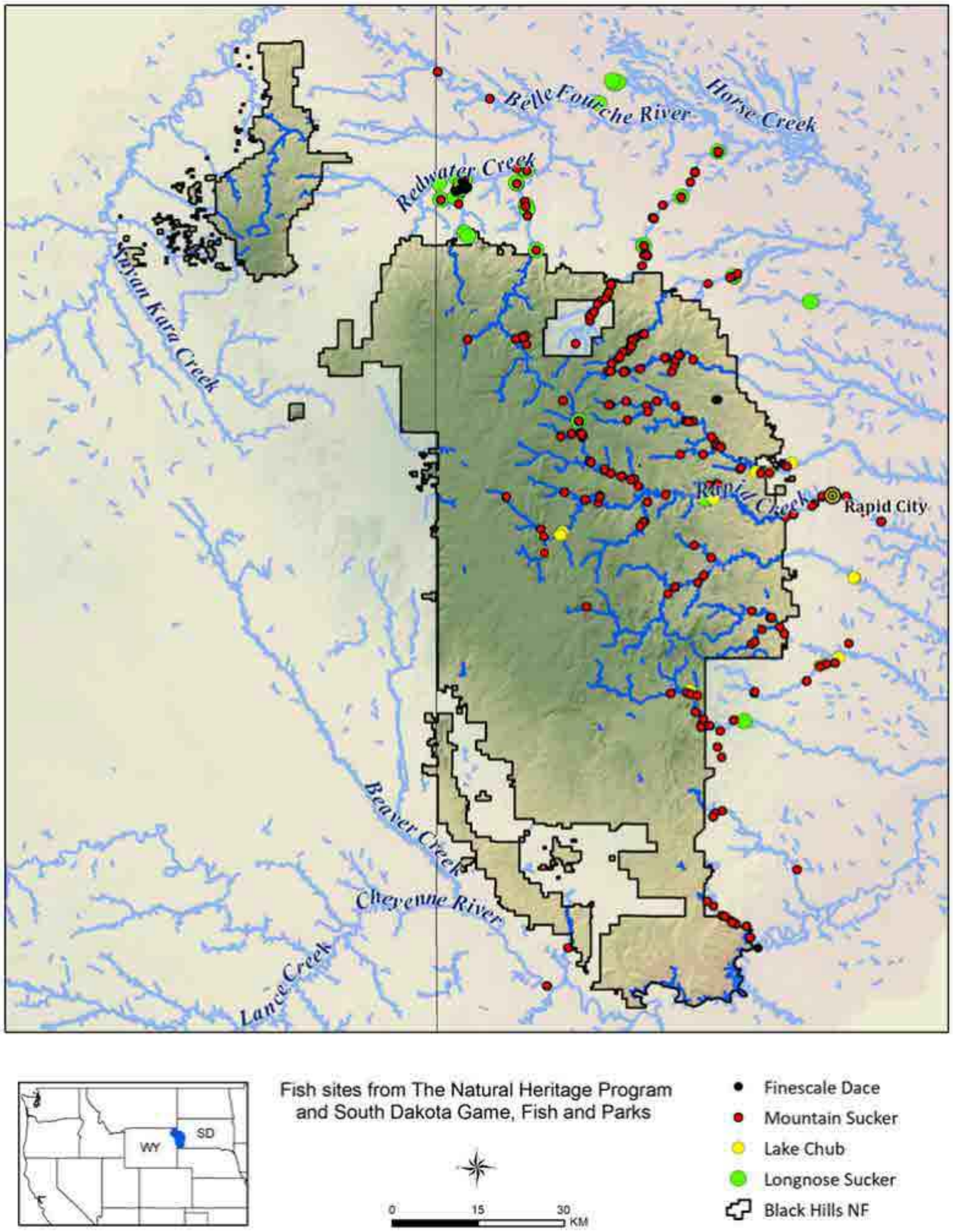

Figure 4-1. Distribution of finescale dace, mountain sucker, lake chub, and longnose sucker on the Black Hills National Forest (NF). Data are from the South Dakota Department of Game, Fish, and Parks database (https://ert.gfp.sd.gov/content/map).

5. Vegetation

Thomas Timberlake and Emily Fusco

Introduction

Ponderosa pine (*Pinus ponderosa*) forests dominate much of the Black Hills, but its forests also include other species, including bur oak (*Quercus macrocarpa*) and aspen (*Populus tremuloides*) (Graham et al. 2021). Notably, the Black Hills hosts isolated populations of several species near the limits of their range, including paper birch (*Betula papyrifera*), white spruce (*Picea glauca*), lodgepole pine (*Pinus contorta*), and limber pine (*Pinus flexilis*). These populations have persisted from the Pleistocene, and both species have present-day ranges primarily concentrated in colder regions in the north (Hoffman and Alexander 1987). As climate change progresses, the extent to which the Black Hills National Forest (Black Hills NF) continues to support these species is an important question. Disturbances affecting the forests of the Black Hills include wildfire, insects, and weather (Graham et al. 2021).

Projected changes in climate will directly affect forest vegetation in the Black Hills by altering vegetation growth, vigor, mortality, and regeneration. Climate change will also have indirect effects on forest vegetation through changes in disturbance regimes and altered ecosystem processes (Bonan 2008; Hansen and Phillips 2015; Hansen et al. 2001; Notaro et al. 2007). The vulnerability of forests to these changes will depend on current conditions of the landscape as well as the legacy effects of past management. Management and planning decisions in the present day thus will affect the long-term trajectories of climate-driven vegetation change. Understanding the vulnerability of ecosystems to climate change is important for managing for ecological integrity, a key concept in U.S. Forest Service planning (36 CFR 219; Timberlake et al. 2018).

This chapter provides a high-level synthesis of the science on climate change and forests. It then synthesizes available information on the vulnerability to climate change of a set of focal tree species important for the Black Hills NF that were identified in collaboration with the planning team.

Climate change effects on trees and forests

This section summarizes climate change effects on trees and forests. Increased temperatures and earlier snowmelt may result in longer growing seasons particularly for forests at higher elevations; however, for water-limited forests found at lower elevations, including ponderosa pine forests, increased temperatures will result in drought stress and decreased tree growth. Drought stress also makes trees more susceptible to mortality from disturbances such as insect outbreaks. Climate-driven extreme weather events will contribute to large-scale ecological disturbances, resulting in acute changes to ecosystem structure, composition, and function (Vose et al. 2016). Climate change may affect tree reproduction for some species; specifically, evidence suggests that drier forests may produce less viable cone crops because of water stress (Ibáñez et al. 2007; LaDeau and Clark 2001). These effects at the tree level affect the overall structure, composition, and function of forests, which, in turn, will have effects on ecological integrity.

Climate change effects on disturbance processes

Disturbance regimes are important system drivers, affecting ecosystem structure, composition, and function. However, climate change can alter disturbance regimes such that these disturbances impair ecological integrity and thus function as system stressors (Timberlake et al. 2018). Most impacts of climate change on forests will occur indirectly through effects on disturbance processes (Keane et al. 2015; McKenzie et al. 2009; Peterson et al. 2014).

<u>Drought</u>

Warming temperatures are likely to result in drought conditions having more substantial adverse impacts on forests (Vose et al. 2016). Hot droughts (droughts accompanied by extreme and prolonged heat waves) present a particular challenge. At higher temperatures, there is increasing evapotranspiration demand, which can make the effects of a lack of moisture more acute in terms of reduced growth and increasing mortality rates (Frankson et al. 2017). Across the western United States, years with high acres burned correlate with years with drought conditions, and, so, increasing drought under climate change will result in more widespread fire (Peterson et al. 2014).

<u>Insect outbreaks</u>

Warming contributes to outbreaks of endemic bark beetles directly and indirectly. Warmer winters allow more beetles to survive from year to year and contribute to increased reproduction (Graham et al. 2021). In addition, climate-driven drought conditions can weaken tree defenses against bark beetles, thus contributing to the potential for epidemic populations. These climate-related factors interact with other factors, such as tree density (Bentz et al. 2010).

<u>Fire</u>

Higher temperatures and altered precipitation patterns affect wildfire patterns. The growing body of research is documenting increases in area burned correlated with changes in climate-related metrics, including decreased fire season precipitation, earlier snowmelt, and warming temperatures (Westerling 2006; Westerling 2016; Holden et al. 2018). Some studies also suggest that increases in area burned due to climate change will also correspond with increases in area burned at high severity (Parks and Abatzoglou 2019) and increases in area burned at high elevations (Alizadeh et al. 2021). This body of research also indicates that firefighters will face longer fire seasons and more fire danger days across the western United States (Rocca et al. 2014; Abatzoglou et al. 2021), which will result in limitations in the availability of firefighters and associated resources. Most of these studies are conducted at a scale of western United States with some including the Black Hills and others excluding the area. However, it is reasonable to expect that the relationships established by these large, West-wide studies are relevant to the Black Hills. This is reflected in a vegetation modelling study conducted for an area in the Black Hills, which indicates that projected future climate conditions will result in more widespread fire (King et al. 2013).

In March 2021, the Schroder Fire burned around 2,200 acres of primarily private lands adjacent to the Black Hills NF and just west of Rapid City, concurrent to another smaller fire burning near Mount Rushmore. These fires occurred at a time when the entirety of the Black Hills region was under at least a Moderate Drought (D1) classification with some areas under a Severe Drought (D2) classification (National Drought Mitigation Center 2021). The fire and associated drought conditions led the Governor of South Dakota to declare a state of emergency (Governor of South Dakota 2021). Similarly, the Jasper Fire, which burned over 80,000 acres in the Black Hills in 2000, occurred during a period of extreme drought and associated extremely low fuel moistures (Lentile and Smith 2006). While these individual fire events cannot be attributed to climate change, they demonstrate the potential types of impacts of climate change on fire that managers may face in a future with more frequent, prolonged drought conditions and variable precipitation patterns due to climate change.

Species assessments

This section synthesizes information on climate change impacts on several important species for the Black Hills NF.

Ponderosa pine (*Pinus ponderosa*)

Ponderosa pine is a drought- and fire-adapted conifer species found throughout the western United States generally in lower montane areas. Historically, ponderosa pine forests in the Black Hills experienced relatively frequent low- and medium-severity fires, which resulted in open, park-like conditions in most places. However, ponderosa pine forests in the Black Hills historically had greater heterogeneity and more dense patches than ponderosa pine forests in other regions, especially the Southwest. A century of fire exclusion has significantly altered forest structure in ponderosa pine forests around the West, including in the Black Hills (Brown et al. 2006; Brown and Cook 2006; Graham et al. 2021).

Ponderosa pine is one of the six ecosystem types covered in the terrestrial and aquatic ecosystems vulnerability assessment for the Rocky Mountain Region (Rice et al. 2018). The vulnerability assessment determines with high confidence that ponderosa pine ecosystems have moderate vulnerability to climate change in the Rocky Mountain Region, which includes Ponderosa pine populations in the Black Hills, Front Range of Colorado, and Southwest Colorado.

Climate exposure. Key aspects of ponderosa pine exposure to climate change include variability in annual and seasonal precipitation, warmer temperatures, more frequent and intense drought, and a longer growing-season. Given their widespread range, ponderosa pine is adapted to a wide range of moisture availabilities, though decreases in moisture availability may be particularly impactful to regeneration. Drought conditions may also make trees more susceptible to other disturbances, including insects (Rice et al. 2018). Ponderosa pine growth in the Black Hills correlates with snowpack (Gleason et al. 2021).

Regeneration. In the Black Hills, year-round precipitation along with high levels of growing-season precipitation contribute to prolific regeneration and growth (Graham et al. 2021; Rice et al. 2018; Shepperd and Battaglia 2002). Dendrochronological studies indicate that wet periods resulted in synchronous recruitment of trees across large areas in the Black Hills (Brown 2006). Although mature ponderosa pine are generally drought-tolerant and fire-adapted, the species is particularly sensitive to drought conditions during seed germination and establishment. Mature trees can also be sensitive to a lack of moisture availability during cone development and masting periods (Rice et al. 2018). As such, decreases in available moisture due to climate change, particularly during the growing season, could reduce regeneration in the Black Hills.

Climate projections for the Black Hills are generally uncertain for precipitation but suggest that there may be an increase in winter and spring precipitation, which could potentially benefit the species. However, projections show wide variation in future precipitation and increased variability in year-to-year moisture availability and precipitation may be particularly important. Especially when to compared to other areas of ponderosa pine forests, the Black Hills generally have consistent periods of reliable moisture thus allowing for seed development and germination. Variability in moisture availability from year to year may result in increased variability in regeneration and growth compared to the present.

Species range. Ponderosa pine ecosystems are widespread throughout the western United States. The Black Hills population is well north of the southern range limits of the species. These factors suggest a low vulnerability. However, the Black Hills may lack higher elevation areas for upslope range shifts in ponderosa pine forests. The lower elevation ecotones for ponderosa pine in the Black Hills may also be vulnerable to vegetation type conversion to grasslands, especially following disturbances. The Black Hills population is one of the most eastern ponderosa pine populations. This does not directly affect climate vulnerability; however, the fact that the population is somewhat isolated from other populations may limit connectivity (Rice et al. 2018).

Disturbances and climate change: fire. Ponderosa pine forests are adapted to relatively frequent, low and medium severity fire. However, Black Hills ponderosa pine forests have longer fire return intervals than populations in other places (Brown 2006; Rice et al. 2018). Several dendrochronological studies have investigated historic fire regimes in the Black Hills; collectively, these studies suggest a mean fire return interval between 10 and 31 years absent fire suppression (Brown and Sieg 1996; Brown and Sieg 1999; Brown et al. 2008; Graham et al. 2021; Hunter et al. 2007). One study using a global vegetation model parameterized for the Black Hills indicates that ecotonal areas between prairies and woodlands are projected to experience increased fire frequencies under projected 21st century climate. This study found that ponderosa pine would continue to persist in these areas in the face of increased fire frequency due to their thick bark and other adaptations that confer resistance to surface fire (King et al. 2013). This study's conclusions countered the findings of climate envelope modelling, which projected a loss of Ponderosa pine in the Black Hills region (Rehfeldt et al. 2006). Mechanistic models like that used by King and others (2013) are generally viewed as more robust than climate envelop modelling (Iverson and McKenzie 2013).

As discussed above, studies conducted across the West indicate that fire will become more widespread as a result of climate change. Ponderosa pine has species functional traits that confer relatively high resistance to fire (Stevens et al. 2020). As such, ponderosa pine may be resilient to climate-driven changes to fire regimes in the Black Hills; however, this will also depend on how current forest conditions contribute to fire risks. Notably, the legacy effects of fire exclusion have resulted in dense stands and surface fuel accumulation that leaves ponderosa pine forests susceptible to fires that burn uncharacteristically large areas at high severity (Brown 2006).

The effects of drier conditions on post-fire regeneration are another well-documented climate change vulnerability for ponderosa pine forests, particularly following fires that burn large areas at high severity. Large areas of high severity fire limit the availability of seed trees and climate-driven drought conditions make it difficult for trees to establish (Stevens-Rumann et al. 2016). Studies examining the effects of the Jasper Fire, which burned over 80,000 acres in 2000, suggest limited regeneration in areas that burned at high severities (Lentile et al. 2005). One study that examined several fires, including the Jasper, indicated that climatic stress was one of three factors most strongly associated with post-fire regeneration patterns, along with burn severity and elevation (Korb et al. 2019).

Disturbances and climate change: insects. Climate change also indirectly and directly affects insect disturbances that affect ponderosa pine. Mountain pine beetles (*Dendroctonus ponderosae*) are endemic to ponderosa pine forests in the Black Hills; however, warmer winter temperatures facilitate the survival and population growth of mountain pine beetles. Drought stress also increases trees' susceptibility to pine beetles (Bentz et al. 2010; Rice et al. 2016). The Black Hills, like many areas in the western United States and Canada, experienced a significant mountain pine beetle epidemic in the early 2000s, which resulted in large amounts of ponderosa pine mortality (Negrón et al. 2017; Steen-Adams et al. 2021).

White spruce (*Picea glauca*)

White spruce is a shade-tolerant, slow-growing species. In the Black Hills, it is found primarily in colder and wetter sites, including north-facing slopes, higher elevations, and colder drainages. Some expansion of white spruce in the Black Hills may have occurred due to fire exclusion over the past century (Hoffman and Alexander 1987; Parrish et al. 1996). The Black Hills population is isolated from the rest of the species' range and is the southernmost population of white spruce, as well as the westernmost population within the United States.

Climate change vulnerability information specific to white spruce in the Black Hills is not available. The research on climate change impacts on white spruce is primarily focused on boreal forests in Canada and Alaska.

Climate exposure. Research conducted in boreal forests indicates that white spruce is not well-adapted to drought conditions, and a lack of moisture availability limits growth in the species (Hynes and Hamann 2020; McGuire et al. 2010; Sang et al. 2019). One study indicated that different provenances of the species show little geographic differentiation in terms of their vulnerability to drought (Sang et al. 2019).

Species range. The Black Hills white spruce population represents a spatially disjunct population of the species that is much farther south from the rest of the species' range. This suggests that the population may be particularly vulnerable as suitable climate for the species shifts up in latitude. However, it may be that the colder, wetter sites that the species already occupies in the Black Hills will continue to function as refugia for the species into the future.

Disturbances and climate change. White spruce is vulnerable to fire as it has relatively thin bark and branches near the ground. White spruce has likely expanded in range in the Black Hills since European settlement as a result of fire exclusion (Parrish et al. 1996). More widespread fire as a result of climate change thus may reduce the prevalence of white spruce on the landscape, particularly in places where the species has expanded due to fire exclusion, including drier meadows. However, if fires do not reach colder, wetter sites, these sites may continue to function as refugia.

Aspen (*Populus tremuloides*)

Quaking aspen is the most prevalent deciduous tree in the Black Hills. Aspen is shade-intolerant and resprouts following disturbances, including fire. In the Black Hills, fire exclusion and ungulate grazing have adversely impacted aspen. Aspen populations in the Black Hills are not currently in decline; however, decreases in regeneration have been documented in recent years (Parrish et al. 1996; Blodgett et al. 2020).

Climate change vulnerability information specific to aspen in the Black Hills is not available; however, vulnerability assessments developed for other regions in the western United

States summarize key factors affecting aspen vulnerability to climate change, which are summarized below.

Climate exposure. Key aspects of aspen exposure to climate change include changes in moisture availability, increasing durations and severity of drought, and extreme temperatures (Rice et al. 2017). In general, moisture stress is a significant driver of aspen mortality, and severe drought events are associated with aspen dieback. Aspen in more xeric sites is particularly vulnerable (Frey et al. 2004; Worrall et al. 2013). In the Black Hills, current aspen distribution is correlated with moisture availability, and thus may change as climate change reduces moisture availability (Shepperd and Battaglia 2002). High temperatures also directly affect aspen. Although aspen photosynthesis increases with temperature between 5 and 25 degrees Celsius, photosynthesis rates decrease above 25 degrees Celsius (around 77 degrees Fahrenheit; Lieffers et al. 2001; Rice et al. 2017).

Species range. Aspen is widespread in the United States with considerable distribution as far south as Arizona (Rice et al. 2017). Although the Black Hills aspen population is somewhat geographically distinct from other populations, it is not at the southern edge of the species' distribution. On the Black Hills NF overall, aspen is the second most abundant tree species, particularly at elevations between 5,000 and 7,000 feet. Below 5,000 feet, bur oak is more abundant than aspen (Walters et al. 2011). Aspen stands in the Black Hills are primarily located on north-facing aspects or in sites that otherwise have wetter conditions (Severson and Thilenius 1976). These types of sites may continue to support the species under warmer drier future climates; however, the fact that the species already occupies the upper elevational range of the Black Hills and its preference for these specific wetter site types suggests that it may be vulnerable to drier future conditions.

A study using bioclimate envelope modelling of aspen habitat suitability found that mean maximum temperature in the warmest month and total precipitation between April and September were the two most important predictors of habitat suitability. This study projected habitat suitability under future climate scenarios and found that suitable habitat would largely be lost in the Black Hills (Worrall et al. 2013). However, bioclimate modelling has inherent limitations due to the fact that these methods rely on historical climate relationships and do not account for ecological processes (Iverson and McKenzie 2013). As such, the results of the bioclimate envelope modelling may have limited utility in explaining future aspen distribution in the Black Hills.

Disturbances and climate change. Fire generally promotes aspen as the species resprouts following disturbance. Frequent fires reduce conifer competition (Rice et al. 2017). One study examining aspen response to the Jasper Fire in the Black Hills suggests that high severity fire is especially beneficial to aspen clones (Keyser et al. 2005). Thus, aspen may benefit from ongoing and projected increases in area burned due to climate change, especially if these trends include an increase in area burned at high severity. Aspen forests may also function as firebreaks, given their high fuel moisture (Rice et al. 2017).

However, aspen is vulnerable to the severe drought conditions that also drive increases in fire (Rice et al. 2017; Worrall et al. 2013). Aspen expansion resulting from more widespread fire may thus be moderated by drought-caused mortality.

Bur oak (Quercus macrocarpa)

Species description. Bur oak is a drought and fire tolerant tree (Sieg 1991) in the white oak group. It is common in the central and eastern regions of the United States. In the Black

Hills, the species typically occurs as an understory shrub/tree in upland habitat with ponderosa pine, or as an overstory tree in riparian and lower elevation areas (Sieg 1991, Shepperd and Battaglia 2002). Bur oaks in the Black Hills are smaller than their eastern counterparts (Deitschman 1958), remaining shrubby under some conditions and growing largest along moist ravines and riparian areas (Sieg 1991).

Climate exposure. There is little work that examines climate change effects on bur oak in the Black Hills or within South Dakota generally. However, several climate change vulnerability assessments conducted for the Midwest indicate that bur oak will remain stable or increase under climate change, suggesting that the species will tolerate warmer conditions and drier growing seasons (Swanston et al. 2011, Janowiak et al. 2014, Handler et al. 2014, Brandt et al. 2014). However, it is important to note that Black Hills bur oaks are already living at the western edge of their range, and it has been suggested that their smaller size in this region may be due to already suboptimal conditions (Sieg 1991).

Regeneration. Bur oaks are wind pollinated, with acorn dispersal primarily carried out by small animals such as blue jays and rodents (Deitschman 1958). Bur oak acorn size decreases along a latitudinal gradient, and it is believed that size is directly related to environmental variables, with oaks in drier, colder sites producing significantly smaller acorns (Koenig et al. 2009). Larger acorns may be advantageous for regeneration as seedlings from these acorns may be able to grow larger before photosynthesis is required (Liang 1966). Prime acorn producing age is typically 75-150 years old (Deitschman 1958). Bur oak trees also resprout readily after fire and cutting, but resprouting decreases with tree age (Deitschman 1958, Sieg 1991).

Species range. Bur oak is found primarily in the central and eastern United States, ranging south into Texas, north into Canada, and reaching its western most distribution in the Black Hills (Shepperd and Battaglia 2002). The species is not at the southern edge of its range in the Black Hills. It tends to occupy lower elevations, and higher elevation areas are available for bur oak to track a changing climate. However, the Black Hills is at the western edge of the species' range and conditions may already be suboptimal for the species as evidenced by their smaller size in the Black Hills compared to populations located farther east (Sieg 1991).

Disturbance and climate change. Bur oak is fire tolerant due to its thick bark, and its ability to resprout after burns suggests that it may fare well even under increased fire conditions (Sieg 1991, Swanston et al. 2011). It has also been suggested that disturbance, such as fire or cutting, is necessary for bur oak regeneration, although prescribed burn experiments in the Black Hills showed increased rates of bur oak sprouting rates but not seedling density (Sieg 1991). This is consistent with work in Minnesota bur oak savannas which suggested bur oak seedling density is not affected by increases in fire frequency (Peterson and Reich 2001).

Precipitation extremes leading to drought and flood events may also affect bur oak health. Bur oak is drought tolerant, although drought, combined with additional stressors, such as grazing, may cause species decline (Sieg 1991). Indeed, grazing was linked to species decline in the Black Hills (Shepperd and Batigglia 2002). In the southeastern region of the Black Hills, livestock and wild ungulate grazing pressure may be responsible for low recruitment of bur oak (Ripple and Beschta 2007). Although drought alone can also negatively impact bur oak growth, one study in Minnesota suggested high levels of atmospheric carbon dioxide may help bur oak tolerate drought stress (Wyckoff and Bowers 2010). Bur oak is sensitive to flooding, and in Missouri, the species experienced reduced shoot growth and seedling survival in flood conditions (Kabrick et al 2012).

Bur oak blight (caused by *Tubakia iowensis*) is most severe in the var. *oliviformis* and causes leaf vein necrosis and leaf death (Harrington et al. 2012, Harrington and McNew 2016). In Iowa, wetter springs caused by climate change have been linked to severe bur oak blight outbreaks (Harrington et al 2012). Although bur oak blight has been documented in eastern South Dakota (Harrington and McNew 2016) there is no apparent documentation in the Black Hills NF, suggesting it is currently a low-level threat.

Rocky Mountain juniper (*Juniperus scopulorum*)

Rocky Mountain juniper is a drought-tolerant species that grows in dry climates. It has relatively shallow but widespread roots. In South Dakota, the species is often found in terrain that is steeper and more rugged than neighboring grasslands (Rumble and Gobeille 1995; Sieg 1988). Juniper is also found in ponderosa pine dominated forests and woodlands in the Black Hills (Shepperd and Battaglia 2002).

Climate change vulnerability information specific to juniper in the Black Hills is not available; however, vulnerability assessments developed for other regions in the western United States summarize key factors affecting juniper vulnerability to climate change, which are summarized below.

Climate exposure. Juniper is a drought-tolerant species and will likely not be affected by reduced soil moisture resulting from climate change. Climate change effects on fire are more likely to affect juniper. However, high temperatures can negatively impact juniper growth and regeneration (Halofsky et al. 2018)

Species range. Juniper has a widespread range throughout the Rocky Mountains, including populations located far to the south from the Black Hills. While the Black Hills population is relatively far east in its range, there are other populations nearby in South Dakota and Wyoming (Rumble and Gobeille 1995; Sieg 1988).

Disturbances and climate change. Juniper is drought tolerant and is not to expected to be significantly harmed by intensified drought due to climate change. Although mature juniper can survive low-intensity fires, juniper younger than around 20 years are particularly susceptible to fires. More frequent fires resulting from climate change may thus have significant adverse effects on juniper (Halofsky et al. 2018).

Paper birch (*Betula papyrifera*)

Paper birch is a shade-intolerant, early seral hardwood (Safford et al. 1990). This medium-sized, fast-growing tree typically lives less than 200 years. Although paper birch can be found growing in mono-typic stands post disturbance, it most commonly grows within mixed hardwood-conifer forests (Safford et al. 1990). In the Black Hills, paper birch is typically found as an understory tree growing with aspen, beaked hazelnut, and bur oak, or occasionally as an overstory tree with ponderosa pine. (Shepperd and Battaglia 2002).

Climate exposure. Paper birch is a northern hardwood species adapted to cold climates, and typically does not grow in areas where average July temperature averages exceed 70°F (Safford et al. 1990). Climate projections for the Black Hills indicate that average minimum temperatures for July will increase from the historical mean (1950-2013) of 55°F to 60°F, while average maximum temperatures will increase from 85°F to 90°F. Although there is little work that examines paper birch vulnerability to climate change in the Black Hills, assessments in the eastern United States determined with high confidence that suitability for paper birch will decrease, or severely decrease with a changing climate in these regions (Butler-Leopold et al.

2018, Swantson et al. 2011, Handler et al. 2014, Janowiak et al. 2014). Paper birch is adaptable due to its ability to regenerate after fire, to disperse readily, and to live in a wide range of habitats. However, it is vulnerable due to its susceptibility to being top killed by fire, as well as its shade and drought intolerance (Butler-Leopold et al. 2018). While paper birch can persist in a wide variety of precipitation amounts and patterns (Safford et al. 1990), it is likely moisture limited in the Black Hills (Sieg 1990), and further declines in moisture availability would decrease suitability.

Regeneration. Paper birch seed production can begin as early as 15 years of age and peaks at 40-70 years (Safford et al. 1990). When growing in stands, trees usually produce large amounts of seed every other year (Safford et al. 1990). Although seeds are wind dispersed with high potential dispersal ability, they typically fall near the parent tree and germinate on the soil surface (Safford et al. 1990). Paper birch regeneration success can be affected by environmental conditions. For example, one study from Minnesota suggested that seedling growth decreased in a temperature warming experiment (Reich et al. 2015). Another study in Wisconsin found that increased levels of carbon dioxide increased flowering, seed weight, germination rates, and seedling vigor (Darbah et al. 2008). However, elevated carbon dioxide, in combination with elevated ozone, led to decreased germination rates (Darbah et al. 2008). In addition to reproduction by seed, paper birch can resprout in response to fire and cutting (Safford et al. 1990).

Species range. In North America, paper birch extends in the Northwest from Alaska to the Northeast in Newfoundland and Labrador in Canada (Safford et al 1990). The southern portions of its range are from Oregon in the west to New England and Pennsylvania in the east, with spotty populations occurring as far south as western North Carolina (Safford et al. 1990). In South Dakota and Wyoming, paper birch occurs primarily within the Black Hills region (Safford et al. 1990) at high elevation sites (Sieg 1990). Paper birch in the Black Hills exists as a small, disconnected population in the southernmost portion of its central U.S. range, suggesting that it would be difficult for the species to expand to adjacent locations with a changing climate.

Disturbance and climate change. Individual paper birch trees are not resistant to fire as their papery bark is highly flammable and they are susceptible to top kill; however, stands of paper birch can be resistant to fire and the species rapidly regenerates in burned areas (Hutnik and Cunningham 1965, Safford et al. 1990, Butler-Leopold et al. 2018). Climate change may affect post-fire paper birch regeneration. At its southern range limits in Canada, post-fire paper birch recruitment is expected to be negatively impacted by warming temperatures (Boucher et al. 2020). This is consistent with modeled paper birch abundance in Wisconsin that suggested increased fire frequency combined with warming temperatures decreased birch abundance (He et al. 2002).

Paper birch is susceptible to multiple insect pests including birch leaf miner (*Fenusa pusilla*), and bronze birch borer (*Agrilus amius*) (Safford et al. 1990, Handler et al. 2014). Birch leaf miner causes minor damage, and has not been documented in South Dakota, so it is of little concern (USDA Forest Service 2019). Bronze birch borer is a native wood boring insect found throughout most of North America, including South Dakota. This insect has periodic outbreaks, causing birch mortality. Mortality from these outbreaks is expected to increase under climate change as trees become more drought-stressed (Muilenberg and Herms 2012).

Paper birch is also vulnerable to some root rotting pathogens such as the root rotting fungi such as *Armillaria* and white mottled rot (*Ganoderma applanatum;* Safford et al. 1990, Lockman et al. 2016). These fungi make trees susceptible to toppling and may also reduce growth (Safford et al. 1990, Lockman et al. 2016). Negative effects from pathogens may increase with climate change where trees are already drought stressed (Lockman et al. 2016).

Aquatic ecosystems: low-gradient mountain stream reaches

The regional ecosystem vulnerability assessment for the Rocky Mountain Region of the National Forest System addresses the vulnerability of low-gradient mountain stream reaches, an aquatic ecosystem relevant to the Black Hills NF (Rice et al. 2018).

Low-gradient mountain streams have slopes less than two percent and pass through relatively broad valley bottoms. Large riparian areas and floodplains regulate water flows. Deposition of sediment and organic matter from upstream source segments occurs in low-gradient mountain streams and associated valleys. Riparian vegetation plays an important role in the function of these systems, and they offer important habitat for fish, aquatic invertebrates, and other species, including beaver. Dams, modifications to hydrology, and overharvest of beavers have significantly impacted these ecosystems (Rice et al. 2018).

Low-gradient mountain stream reaches are particularly prominent in the Black Hills NF, which has the largest share (24 percent) of these stream reaches of national forests in the Rocky Mountain Region. Around 30 percent of stream miles in the Black Hills NF fall in this category (Rice et al. 2018). On the Black Hills NF, these perennial streams provide habitat for key fish species, including mountain sucker and finescale dace (see Chapter 4).

The vulnerability assessment determined that low-gradient mountain reaches have very high vulnerability. Specific factors contributing to this determination include:

- The current extent of low-gradient stream reaches is limited and warming temperatures may lead to increasingly fragmented habitat for fish.
- Increasing stream temperatures may harm fish and other aquatic species adapted to specific thermal regimes.
- Low-gradient mountain stream ecosystems are highly dependent on snow-driven hydrological regimes. A shift from snow-dominated to rain-dominated watersheds may significantly alter these systems.
- These stream reaches are vulnerable to droughts, flooding, and other extreme climatic events. Flooding may result from extreme precipitation events, earlier snowmelt, and post-fire watershed impacts.
- Various features of low-gradient streams contribute to their ability to adapt to impacts of climate change. Wide valley bottoms slow water flows and sediment transport. Riparian vegetation stabilizes streambanks and provides shade that reduces stream temperatures. Large wood features in streams helps to regulate flows, and beavers (*Castor canadensis*) may contribute to resilience in these systems.

Summary for forest vegetation vulnerability

Information on species vulnerability coupled with climate projections provides insights on how climate change functions as a system stressor and driver to ecosystems in the Black Hills. Overall, available information suggests that ponderosa pine will continue to remain the dominant tree species in the Black Hills NF. Given its drought and fire tolerance, the species is reasonably well-suited for future conditions. However, changes in moisture availability and disturbance regimes may impact growth and mortality rates of the species, and large high-severity disturbances may adversely impact regeneration patterns.

The Black Hills NF contains several species that resprout following fire, which prove beneficial if fire becomes more prevalent in the future. However, increases in drought and temperature may present challenges to two of these species, aspen and paper birch. Paper birch, along with white spruce, are two species with isolated populations in the Black Hills located well south of the remainder of their species range. As such, these two species are likely particularly vulnerable to changes in climate. Even so, the Black Hills may continue to support refugia population of these species, particularly in colder, wetter locations.

Current forest conditions and how they reflect fire exclusion and other past management will impact changes in forest conditions due to climate change. Denser, more homogenous ponderosa pine stands may be particularly vulnerable to impacts from drought and fire. Species like white spruce may currently occupy sites that they are not well suited for as a result of long-term fire exclusion.

This chapter addresses climate vulnerability at the level of the individual species; however, it is also important to consider how climate change will affect overall ecological integrity and key ecosystem characteristics pertaining to the structure, function, and composition of forest and riparian ecosystems on the Black Hills NF. In general, management strategies that promote landscape diversity, in terms of age class, structure, and species composition, provide for resilience to climate change and its impacts on wildfire, insects, and other disturbances.

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6. Recreation

David L. Peterson

- Higher temperatures will extend the duration of the season favorable for warm-weather recreation (nature viewing, hiking, camping, etc.), thus increasing the number of people engaged in warm-weather activities, assuming that roads and facilities are accessible. This will increase stress on facilities and increase demands on recreation staff.
- More extreme-heat days will increase demand for water-based recreation. Lakes where visitation is already high may face increased pressure for access and facilities.
- Increased frequency and extent of wildfires will reduce access to recreational opportunities and negatively affect visual aspects of recreation experiences; smoke will affect human health, potentially over several weeks in the summer.
- Trout populations in streams may be stressed by more variable stream levels, which will affect the distribution of desirable species for angling. This may occur to a lesser extent in lakes.
- Increased frequency of extreme flood events adjacent to streams may damage campgrounds and roads, thus reducing access for recreation.
- As snowpack declines in the future, snow-based recreation (snowmobiling, cross-country skiing, downhill skiing,) will have fewer opportunities, especially at lower elevations.
- The effects of climate change on hunting will probably be minimal, although increasing wildfire could improve habitat for mule deer and white-tailed deer, thus improving harvest success.

A projected increase in warm-weather recreation will be the most important effect of climate change on recreation in Black Hills National Forest (NF), with social, economic, and organizational implications. Higher visitor use will create increasing demands for recreational facilities with limited capacity. In addition to increased opportunities for recreation, potential outcomes include: (1) degraded natural resource conditions, (2) degraded recreational facilities, and (3) increased expectations for forest staff to provide access to facilities and services, maintain facilities and infrastructure, and ensure visitor safety.

Introduction

Benefits of Recreation

As climate change continues to affect ecological systems, the services that humans derive from those systems are affected as well (Miller et al. in review). Outdoor recreation is one of the primary ways in which humans benefit from the continued production of ecosystem services (Haines-Young and Potschin 2012). Through outdoor recreation, individuals are able to obtain a variety of non-material benefits such as educational opportunities, psychological restoration, and feelings of spirituality. These recreational services are important to individuals' lives and to the economies of communities and regions that rely on outdoor recreation and tourism (Hermes et al. 2018).

The benefits of nature-based physical recreation include an offset to sedentary activities, improved psychological well-being, and stress relief. In addition, increased physical activity in recreation settings is associated with lower health care expenditures. These benefits are especially important for vulnerable communities and those from lower income groups who tend to have minimal access to high-quality health care, tend to have more health risks, and are underrepresented in outdoor recreation, especially on federal lands (Winter et al., 2020).

Outdoor recreation contributes to long-term societal sustainability by providing spillover effects such as increased attachment to and appreciation for nature, and development of long-standing environmental attitudes that promote pro-environmental behaviors. If climate change alters accessibility to various outdoor recreation activities, locations, and seasons, human health benefits will also shift, as will adaptive capacity for individuals and organizations.

Outdoor recreation contributes to the U.S. economy, generating $887 billion in consumer spending and 7.6 million jobs annually (The Outdoor Foundation 2018). The economic value of recreation represents the "reward" that recreationists receive from engaging in a particular activity. This differs from the economic impact of recreation, which measures how spending by recreationists affects local economies. For recreationists who recreate in national forests in the U.S. Forest Service (USFS) Rocky Mountain Region (Colorado, Kansas, Nebraska, South Dakota, Wyoming), the annual aggregate economic benefit is $2.2 billion (Rosenberger et al. 2017). However, this economic value is an underestimate of the total benefits individuals receive from outdoor recreation, because national parks, state parks, and other public lands in the Rocky Mountain Region are not included in the valuation.

Recreation Context in Black Hills National Forest

Black Hills NF plays a key role in providing recreation opportunities for both local and non-local recreationists in western South Dakota and eastern Wyoming. The forest is part of a larger complex of outdoor recreation that includes other federal (Forest Service [Thunder Basin National Grassland], National Park Service, Bureau of Land Management) and state (Custer State Park) lands. Some private and tribal lands also provide recreational opportunities and lodging.

Black Hills NF maintains 31 campgrounds with a total of 670 sites, with a wide range of settings and level of development (Fig. 1). Reservoirs and lakes are popular focal points for boating, fishing, and camping, especially in the summer; Pactola Reservoir and Sheridan Lake alone contain nearly a third of all campground sites on the forest. Black Hills NF has 489 miles of trails for non-motorized recreation (including 108 miles of the Mickelson Trail, as well as access to Black Elk Wilderness) and 700 miles of trails for motorized recreation. Paved roads of various jurisdictions (including 66 miles of scenic byways) and unpaved USFS roads provide access to recreational opportunities throughout the forest. Over 500 miles of perennial streams provide opportunities for boating and fishing, including blue-ribbon trout streams. Terry Peak Ski Area is a destination for downhill skiing and snowboarding in winter.

Over 1 million visitors annually visit Black Hills NF to take advantage of diverse recreation opportunities, with a significant positive effect on the economy of local communities. The Black Hills are a unique ecological landscape as the easternmost extent of mountains in the western United States, providing great appeal to local communities as well as travelers on vacation. Along with other public lands and attractions—Crazy Horse Memorial, Custer State Park, Devil's Tower National Monument, Jewel Cave National Monument, Mt. Rushmore National Park, Wind Cave National Park—the Black Hills region provides many places of interest in a relatively small area. Other locations may have more visitors (e.g., Mt. Rushmore

National Park, ~2 million annually), but Black Hills NF, covering 1.2 million acres, provides a regional hub of natural resource and recreational significance in the region.

Forest recreation sites and landscapes in Black Hills NF are used primarily for warm-weather activities (nature viewing, hiking, camping, etc.), so summer and the shoulder seasons in spring and fall are the times when most recreationists visit the forest. Water-based recreation (canoeing, kayaking, water skiing, paddle boarding) is popular on lakes and reservoirs, and some canoeing and kayaking occur on streams. Most fishing occurs on lakes and reservoirs, primarily focused on nonnative trout and other nonnative fish as the target species. Hunting focuses on mule deer and white-tailed deer. Snowmobiling and cross-country skiing are the primary winter activities on the national forest, with downhill skiing available at Terry Peak Ski Area adjacent to the forest.

This high level of visitation in Black Hills NF is a major management responsibility for forest staff in terms of visitor facilities and services, maintenance, and safety. In some cases, heavy use creates stress for aging recreation facilities. Most recreation sites were developed in the 1960s and 1970s, and some buildings and related infrastructure are reaching the end of their engineering design life (Fig. 2). Parking is often insufficient for large numbers of visitors and large vehicles; current recreationists have higher expectations for facility quality (e.g., campground amenities) and space (e.g., for large recreational vehicles) than in the past. Resource damage is increasing in some areas, commensurate with high use levels (Bradley Block, Black Hills NF, personal communication).

A related issue is a recent increase in and demand for off-highway vehicle (OHV) use on national forest roads (Bradley Block, Black Hills NF, personal communication). OHV activities have created conflicts with other recreational activities and user values. Campgrounds are increasingly being used by recreationists with OHVs, who are often negatively perceived by other campground users. Local homeowners also have concerns about the noise and dust caused by OHVs. These types of conflicts create a social and management challenge for forest recreation staff.

In addition, Black Hills NF has not been able to provide forest visitors with sufficient education and interpretation on natural resource issues that would advance their recreational experience and connection to the land (Bradley Block, Black Hills NF, personal communication). This includes topics related to: (1) forest management (including timber harvest), (2) forest dynamics and health (e.g., mountain pine beetle outbreaks), (3) wildfire, including effects of smoke on human health, (4) insect outbreaks in forests, including effects on safety (e.g., in Black Elk Wilderness) (Fig. 3), and (5) wildland-urban interface issues. If recreational use continues to increase, as it did in 2020 in conjunction with the COVID-19 pandemic, it will be difficult to provide educational and safety information to visitors.

Extreme heat, drought conditions, insect outbreaks, and wildfire have demonstrated how rare but extreme events can affect natural resources and visitor experiences in Black Hills NF and beyond. The likely increase in frequency and extent of these events in a warmer climate has elevated the importance of climate change in the Black Hills region (see sections on climate and vegetation) and will almost certainly affect recreational patterns and experiences.

Visitor Demographics and Recreation Patterns

Recent data on recreation are available from the most recent National Visitor Use Monitoring (NVUM) survey conducted at Black Hills NF (USFS 2019). In 2019, 1.1. million people were estimated to have visited various sites on the forest, including the following number of visits by category:

- Day-use developed sites — 215,000
- Overnight use developed sites — 327,000
- General forest area — 424,000
- Designated wilderness —105,000
- Special events and organized camps — 12,000

Visitor satisfaction was very positive, with 82.7% ranking their experience as very satisfied and 15.6% as somewhat satisfied, which is in line with national averages.

Demographic data show that 41% of visits to Black Hills NF are by females. Among racial and ethnic minorities, the most commonly encountered are Native Americans (2.2%) and Hispanic/Latinos (1.6%) (USFS 2019). The age distribution shows that over 25% of visits are children under age 16. People over the age of 60 account for 13% of visits (comparable to the South Dakota population). About 30% of visits are from those living within 25 miles of the forest: over 25% come from people who live 25 to 50 miles away. About 30% of visits come from those living more than 200 miles away.

Over half of visits last at most 6 hours, although the average duration is 37 hours. The median length of visits to overnight sites is 25 hours, indicating most are at least a two-night stay. Nearly half of visits come from people who visit at most 10 times per year. Very frequent visitors are not overly common; about 16% of visits are made by people who visit more than 50 times per year.

Warm-weather activities are by far the most common form of recreation in Black Hills NF, including (in order of popularity) viewing natural features, hiking/walking, relaxing, viewing wildlife, driving for pleasure, picnicking, and developed camping (USFS 2019) (Table 6-1). Around 50% of overnight visitors use national forest campgrounds; renting national forest cabins is also popular. About 22% of visitors participate in fishing, and 4.9% participate in hunting. Non-motorized water recreation is also popular (15.0%), but motorized water recreation is less common (1.9%). Motorized land-based activities include trail activity (6.6%) and off-highway vehicle activity (4.9%). Snow-based activities include snowmobiling (2.8%) and cross-country skiing (0.4%).

Recreation in Black Hills NF contributes $45 million per year to the economies of local communities (Table 6-2), of which 73% is from non-local visitors (those who live in ZIP codes 30 miles or greater from the Black Hills NF boundary). The highest spending categories for non-local visitors are motels (34%), restaurants (20%), gasoline and oil (15%), groceries (12%). The highest spending categories for local visitors differ considerably: gasoline and oil (27%), groceries (24%), restaurants (13%), motels (11%).

Effects of Climate Change on Recreation in Black Hills National Forest

Climate change will affect recreation both directly (e.g., higher temperature) and indirectly (e.g., increased wildfire frequency) (Fig. 4). There is general agreement in the scientific literature that warmer temperatures will expand the season for warm-weather recreation, increase demand for water-based recreation on hot days, and shorten the season and area for snow-based recreation (Hand and Lawson 2018; Hand et al. 2018; Hand et al. 2019a,b;

Miller et al. in press, in review; O'Toole et al. 2019, Peterson et al. in press; Winter et al. in press). The consistency of these assessments at multiple locations in the western United States provide a strong basis for inferences about how climate change is expected to affect recreation in Black Hills National Forest. The effects of climate-related hazards, notably wildfire (Bedsworth et al. 2018), on the quality of outdoor recreation has also been assessed, including when recreation sites are closed during and after hazard events (Sánchez et al. 2016, Winter et al. in press).

Effects on Warm-Weather Activities

Warm-weather activities (e.g., hiking, camping, nature viewing) are sensitive to temperature and site conditions, especially the availability of snow- and ice-free sites. Number of warm-weather days (Richardson and Loomis 2004) and mean monthly temperatures are predictors of visitation patterns (Albano et al. 2013, Fisichelli et al. 2015, Scott et al. 2007). Warm-weather recreationists are also sensitive to site quality and characteristics, such as wildflowers in bloom, trail conditions, vegetation, availability of shade, and presence of fire and smoke (Kim and Jakus 2019).

Forested areas are commonly associated with warm-weather activities and are often sensitive to a warmer climate in some locations. Vegetation shifts may indirectly affect recreation oriented toward viewing vegetation types that will be altered or lost in certain areas (e.g., alpine and subalpine scenery), potentially affecting recreationists' decisions to visit the region. For example, under various climate change scenarios, Rocky Mountain National Park visitors who traveled from longer distances were more likely to take fewer trips than those who traveled shorter distances, (Richardson and Loomis 2004).

The effects of climate change on warm-weather recreation participation will likely vary across climate zones. In cooler zones, the supply of warm-weather activities is expected to increase due to increasing season length, with higher temperatures resulting in snow- and ice-free sites being available earlier and later in the year, and an increase in the number of warm-weather days in spring and autumn (Albano et al. 2013, Fisichelli et al. 2015). For example, higher minimum temperatures are associated with an increased number of hiking days (Bowker et al., 2012). However, areas projected to experience more extreme heat may see reduced visitation in some cases (Bowker et al. 2012, Richardson and Loomis 2004, Scott et al. 2007). Extreme heat may shift demand to cooler weeks at the beginning or end of the warm-weather season, or to alternative sites that are less exposed to high temperatures (e.g., at higher elevations or near water bodies).

In some areas, increased frequency and extent of wildfire are expected to reduce the supply of warm-weather activities in certain years due to degraded site desirability, impaired air quality from smoke, and safety-related closures (Miller et al. in press, Peterson et al. in press). Recent wildfire activity generally corresponds with decreased visitation rates but with differential effects on the value of hiking trips (positive) and mountain biking trips (negative) (Loomis et al. 2001; Hesseln et al. 2003, 2004). Recent fires are also associated with initial reductions in camping (Rausch et al. 2010) and backcountry recreation (Englin et al. 1996) that diminish over time. The severity of fire may also matter; high-severity fires are associated with decreased visitation, whereas low-severity fires are associated with slight increases in visitation (Starbuck et al. 2006; Sánchez et al. 2016). Wildfire can also affect the connectivity of long-distance hiking trails (Miller et al. in press).

Reduced air quality from wildfire smoke can affect the quality, timing, and location of recreational visits by non-local visitors (Sage and Nickerson 2017), with reduced recreation by local residents. For example, in 2017, Oregon experienced a severe fire season, with the worst air quality related to wildfire smoke since 2000 (Miller et al., in press). Visitation to Mt. Hood and the Columbia River Gorge decreased by over 4%, accompanied by a 2% loss in visitor spending (Ghahramani 2017). Similar adverse impacts to recreation access in large areas of California were reported in 2018 when the Lake Tahoe Basin was affected by smoke and decreased visibility from the Ferguson Fire. The economic losses associated with this fire, which closed Yosemite National Park for three weeks, was $46 million in visitor spending in Mariposa County (Wilson et al. 2020). Staff on Black Hills NF reported that the most recent large fire in the area, the 83,000-acre Jasper Fire in 2000, produced smoke plumes that were visible from Interstate-90 and may have deterred recreationists from visiting the forest. Even the small Iron Fire, which burned in Black Elk Wilderness in August 2021, required closure of several parking areas and hiking trails.

Effects on Warm-Weather Activities in Black Hills National Forest

- The warm-weather recreation season will be longer, extending further into the spring and fall shoulder seasons.
- More visitors over a longer period of time will increase the need for access to recreational opportunities and facilities, potentially creating additional stress for natural resources (e.g., trampling of vegetation), facilities, and infrastructure.
- More visitors will require forest staff to provide services, maintenance, and safety communications over a longer period of time. This may have implications for seasonal employment and concessionaire agreements.
- The frequency and extent of wildfire will likely increase in the Black Hills region (Fig. 5). This will reduce access to roads, trails, and campgrounds during active fires and possibly afterwards to ensure visitor safety. Smoke from local wildfires and fires to the west will create unhealthy conditions for days to weeks at a time. These fire effects will reduce visitation while fires are burning and perhaps afterwards, depending on fire severity (tree mortality) and availability of facilities. If wildfires are burning elsewhere but not in the Black Hills, recreationists may redirect their travels to the Black Hills region.
- Increased insect outbreaks, especially mountain pine beetles in ponderosa pine, may cause extensive tree mortality, creating safety hazards for a variety of recreationists and affecting scenic qualities
- Because an extended warm-weather recreation season will bring more visitors to the Black Hills region, local communities will derive economic benefits, directly for tourism-based businesses and indirectly for secondary services and supplies. Periodic wildfires will cause episodes of significant decline in business.

Effects on Water-based Activities (Not Including Fishing)

Climate change is expected to affect both supply and demand of water-based activities. The availability of suitable sites for water-based recreation is sensitive to reduced water levels caused by higher temperatures, increased variability in precipitation, and decreased precipitation as snow. Reduced surface-water area is associated with decreased participation in boating and swimming (Bowker et al. 2012, Loomis and Crespi 2004, Mendelsohn and Markowski 2004), and magnitude of streamflow is positively associated with number of days spent rafting, canoeing, and kayaking (Loomis and Crespi 2004, Smith and Moore 2013). Demand for water-based recreation is generally higher when temperature is higher (Loomis and Crespi 2004, Mendelsohn and Markowski 2004), although extreme heat may dampen participation for some activities (Bowker et al. 2012).

Recreation on rivers and smaller streams is vulnerable to the effects of climate change on drought (low streamflow) and wildfire (degraded scenery, reduced access). In some areas, rafters prefer intermediate water levels and warm weather over turbulent, cold spring runoff or late-season low water (Yoder et al. 2014). The period of time when desirable conditions for water-based conditions are available will be affected by a warmer climate and more variable water levels (see hydrology section).

Recreation in lakes and reservoirs may be negatively affected if water levels are reduced by high temperatures, reduced storage of water as snowpack, and increased precipitation variability. Increased demand for surface water by downstream users may exacerbate reduced water levels in drought years. Higher air temperatures are expected to increase the demand for water-based recreation as the viable season lengthens and as people increasingly seek water-based opportunities during episodes of extreme heat, although higher temperatures can also cause harmful algal blooms (Hand and Lawson 2018, Moore et al. 2008). Other climate-related impacts to water quality stem from extreme events that contribute to elevated pollutant loads (Clow et al. 2011).

Effects on Water-based Activities in Black Hills National Forest

- As temperatures increase in summer, water-based recreation will become a more popular activity, especially during periods of extreme heat.
- Higher temperatures will facilitate a longer season for water-based recreation.
- Increased demand for recreation at lakes and reservoirs will create additional competition for parking and camping units. More people and more boats may reduce the quality of the recreational experience.
- More variable streamflows may restrict the amount and/or quality of canoeing and kayaking. Lakes and reservoirs will probably not be as sensitive to variable water levels.
- Increased flooding by streams may disrupt recreation and damage campgrounds and facilities (Fig. 6).
- Lakes and reservoirs may be subject to harmful algal blooms as water temperature increases, creating hazardous conditions for humans and pets (algal blooms have been previously observed in Stockade Lake, Custer State Park).

Effects on Wildlife-based Activities

Wildlife-dependent recreation activities involve terrestrial or aquatic animals as a primary component of the recreation experience, including both consumptive (e.g., hunting) and non-consumptive (e.g., animal viewing, catch-and-release fishing) activities. Wildlife activities depend on the distribution, abundance, and population health of desired target species. These factors influence "catch rates," the likelihood of harvesting or seeing an individual of the target species. Sites with higher catch rates can reduce the time and effort associated with an activity and enhance enjoyment for a given activity (e.g., many views of a valued species).

Catch rates determine site selection and trip frequency for hunting (Loomis 1995, Miller and Hay 1981), participation and site selection for fishing (Lamborn and Smith 2019, Morey et al. 2002), and participation in non-consumptive wildlife recreation (Hay and McConnell 1979).

Altered habitat, food sources, or hydrologic conditions associated with climate change may alter animal abundance and distribution, which in turn influence catch rates and participation in recreation. Where habitat has been altered by wildfire, wildlife-based recreation will likely change due to issues of safety and area closures, as well as (negative and positive) shifts in animal populations. Staff at Black Hills NF noted that the area burned by the Jasper Fire (83,000 acres) in 2001 now provides high quality habitat for elk, mule deer, and white-tailed deer.

Temperature and precipitation are related to general trends in participation for several wildlife activities (Bowker et al. 2012, Mendelsohn and Markowski 2004), although the exact relationships differ by activity and target species. Higher temperatures in the western United States. are expected to increase participation because of an increased number of days desirable for activities such as hunting, birding, and viewing wildlife (Bowker et al. 2012). However, hunting that occurs during discrete seasons may depend on weather conditions during a short period of time within those seasons.

Anglers may experience moderate negative effects of climate change on benefits derived from fishing, especially in areas where cold-water species are the target. Opportunities for catching cold-water species are likely to be reduced as cold-water habitat shrinks to higher elevations and are eliminated, as projected in other areas of the western United States (Isaak et al. 2012). Warm-water tolerant species may increasingly provide targets for anglers, mitigating reduced benefits from fewer cold-water species (Hand and Lawson 2018). Increased frequency and extent of wildfires may increase erosion in some areas, reducing the quality of fishing sites or desirability of angling relative to other activities.

Effects on Wildlife-based Activities in Black Hills National Forest

- As water temperature increases and streamflows become more variable (see Chapter 3), the distribution and abundance of different fish species may change. This will occur over a shorter period of time and more prominently in streams than in lakes.
- The effects of increased water temperature on species that are popular with anglers in streams (especially brook trout, brown trout, and rainbow trout) and lakes (including crappies, perch, and walleyes) will determine whether or not sportfishing is affected. The trout are moderately sensitive to warmer water and could be negatively affected during periods of extreme heat.
- If populations of popular fish decline, the quality of the fishing experience for anglers will also decline.
- It is uncertain how a warmer climate will affect species targeted by hunters—there may be both positive and negative outcomes, depending on species. Increased frequency and extent of wildfire would create habitat that favors mule deer and white-tailed deer.

Effects on Snow-based Activities

Significant declines in mountain snowpack in the western United States have been observed in recent decades, and the proportion of precipitation as snow is projected to decrease below around 6,500 feet elevation for most of the western United States (Mote et al. 2018). The rain-snow transition zone (i.e., where precipitation is more likely to be snow rather than rain for a given time of year) is expected to move to higher elevations, particularly in late autumn and early spring (Klos et al. 2014). Projections specifically for the Black Hills region suggest that the fraction of cumulative snow melt prior to April 1 is expected to increase by over 6% per decade (Musselman et al. 2021). This places all of the Black Hills (highest elevation of 7,241 feet), especially lower elevation sites, at risk of shorter or absent snow-based recreation seasons. Additional information on climate impacts on snowpack is available in Chapter 3.

Snow-based recreation is highly sensitive to variations in temperature and the amount and timing of precipitation as snow (Wobus et al. 2017). Seasonal patterns of temperature and snowfall determine the likelihood of a site having a viable season (Scott et al. 2008). Lower temperatures and the presence of new snow are associated with increased demand for skiing (Englin and Moeltner 2004). Based on high greenhouse gas emission scenarios, downhill skiing and snowmobiling in the United States may lose 12–20% of current visits by 2050, and cross-country skiing visits will decline depending on local snow conditions (Wobus et al. 2017). In areas where participation does not decrease with supply, shorter seasons and smaller snow-covered areas may result in snow-based recreation being concentrated in smaller areas (by around 2050). After 2100, the supply of snow-based recreation areas may disappear from some regions altogether.

<u>Effects on Snow-based Activities in Black Hills National Forest</u>

- The duration of the season for snow-based activities will decrease greatly, especially by the mid to late 21st century (Fig. 7).
- Recreationists will need to go to higher elevations for viable snow. The North Hills area may be the only place where viable snow is available.
- Having fewer areas available with viable snow will force recreation to concentrate on a decreasing number of areas, increasing the density of recreationists and perhaps creating conflicts (e.g., cross-country skiing and snowmobiling may be incompatible).
- Terry Peak Ski Area (summit at 7,100 feet) will have decreasing snowpack available for downhill skiing and snowboarding, resulting in a shorter season, fewer days with good snow, and less terrain with good snow. The ski area will need to increasingly rely on snowmaking in order to maintain operations, assuming that sufficient water is available.

Conclusions

Climate change is expected to have both positive and negative effects on recreation opportunities in Black Hills NF in future decades. A longer season for warm-weather recreation is likely the most important outcome with respect to future planning. This is significant because warm-weather recreation is so popular in the Black Hills region, comprising the majority of visitor activities and economic benefits of recreation. Water-based recreation may become more popular as a way to escape extreme heat in summer. This potential increase in visitors would create demands for access and facilities that go beyond the current capacity of a sustainable recreation program. The effects of climate change on wildlife-based activities are uncertain but will probably have both negative and positive outcomes. Effects on snow-based recreation will be uniformly negative, perhaps in the near future, although this form of recreation has far fewer participants than warm-weather recreation.

The high probability that extreme events, especially drought and wildfire, will become more common in future decades may have an overwhelming influence on how climate change influences recreation. It is possible that the frequency and extent of wildfires may increase so much by around 2050 that fire risk and smoke will be a deterrent to summer recreation, limiting recreation opportunities and affecting the economy of local communities. Additional economic damage to local communities may occur through other climate change impacts that affect how people recreate. For example, drought conditions that result in less access to high-quality opportunities for water-based recreation may increase congestion at viable locations, decreasing satisfaction with recreation experiences and discouraging participation.

Regardless of the effects of climate change on recreation opportunities and recreationist behavior, recreation activities will be affected concurrently by economic conditions and population growth (Askew and Bowker 2018, USFS 2016). One would expect increased demand for recreation in proportion to population increase, although regional differences in demography and economies will modify effects on recreation. Between 2010 and 2020, the population of South Dakota increased by 72,000, and the population of Pennington County increased by 8,000. The U.S. population increased by 7.4% during this period, which is significant because a large proportion of visitors to Black Hills NF are from other states. Unanticipated economic and social factors can create surprises—a good example is the uptick in visitors to public lands during the COVID-19 pandemic.

A significant concern moving forward will be the capacity of existing recreation facilities and staff at Black Hills NF to meet the potential for increasing demand for recreation opportunities in a warmer climate. This is already true at some locations during the peak summer season. Another concern is aging facilities and infrastructure, especially given expectations of current visitors for what they consider adequate to support a high-quality recreation experience. These issues have implications for sustainable recreation planning and for future budget needs.

The good news is that recreationists are generally adaptable to changing conditions. If one activity (e.g., skiing) is not available, they will switch to another activity (e.g., hiking). If a favored location is not available for camping due to a recent wildfire, they will travel farther to another suitable location. Management institutions will need to be equally flexible in finding ways to address the new challenges posed by a changing climate. Internal and external collaboration and communication will help facilitate evolution of sustainable recreation programs in Black Hills NF and the broader Black Hills region.

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Table 6-1. Participation by visitors in various recreation activities in Black Hills NF. Data are from the 2019 NVUM survey (USFS 2019).

Activity	**Participation**[a]	**Main activity**[b]	**Amount of time doing main activity**
	Percent	*Percent*	*Hours*
Viewing natural features	64.0	12.7	8.5
Hiking/walking	61.8	26.5	4.9
Relaxing	58.7	5.7	36.2
Viewing wildlife	57.6	2.4	5.2
Driving for pleasure	46.9	9.5	6.3
Picnicking	25.8	1.6	5.5
Developed camping	24.0	9.6	39.6
Fishing	22.2	11.3	5.2
Non-motorized water	15.0	2.4	2.8
Bicycling	14.7	3.2	2.0
Other non-motorized	14.0	1.6	2.5
Nature study	12.7	0.0	0.0
Nature center activities	12.5	0.0	0.0
Visiting historic sites	9.7	0.3	8.7
Motorized trail activity	6.6	2.2	8.5
Some other activity	5.3	2.0	10.9
Off-highway vehicle use	4.9	0.5	8.1
Hunting	4.9	4.8	21.8
Gathering forest products	4.6	0.0	0.0
Resort use	4.2	0.0	52.5
Snowmobiling	2.8	2.8	4.6
Backpacking	2.7	0.1	70.9
Primitive camping	2.4	0.1	36.8
Motorized water	1.9	1.2	3.1
Horseback riding	0.9	0.0	0.0
Cross-country skiing	0.4	0.0	0.0
Other motorized activity	0.4	0.2	1.8
Downhill skiing	0.0	0.0	0.0

[a] Survey respondents could select multiple activities, so the total in this column is greater than 100%.

[b] Survey respondents were asked to select only one of their activities as the main reason for the forest visit. Some respondents selected more than one, so the total in this column is greater than 100%.

Table 6-2. Estimated total annual expenditures by visitors within 50 miles of Black Hills NF in 2019. Data provided by Eric White (USFS, Pacific Northwest Research Station).

Spending category	**Non-local spending**[a]		**Local spending**[b]	
	Dollars[b]	*Percent*	*Dollars*[b]	*Percent*
Motel	11,126,393	34	1,410,379	11
Camping	1,531,699	5	899,827	7
Restaurant	6,519,998	20	1,735,671	13
Groceries	3,789,127	12	3,522,640	27
Gas and oil	4,810,721	15	3,157,144	24
Other transportation	803,328	2	687,826	5
Entry fees	785,745	2	535,660	4
Recreation and entertainment	1,185,847	4	282,419	2
Sporting goods	765,116	2	763,897	6
Souvenirs and other expenses	1,416,611	4	189,880	1
Total	32,734,586	100	13,185,344	100

[a] Non-local refers to trips by visitors who reported a ZIP code greater than 30 miles from the Black Hills NF forest boundary.

[b] 2019 dollars.

Figure 6-1. Black Hills NF recreation map.

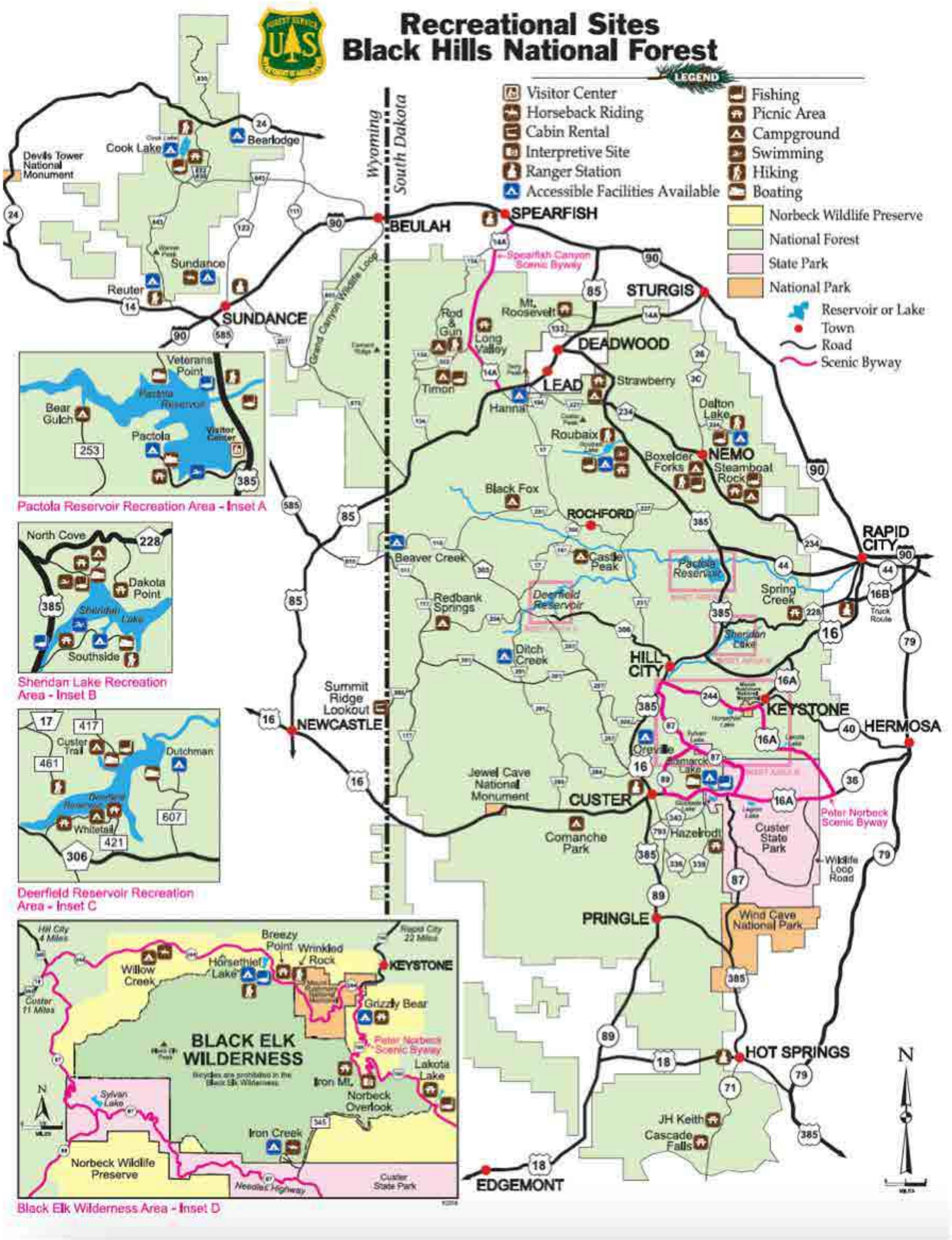

Figure 6-2. Signs at Gold Run trailhead, Black Hills NF. Numerous trailhead signs in the forest are in disrepair and have minimal information on trails and natural resources. Walking surfaces for viewing and access are often unmaintained.

Figure 6-3. Hikers in Black Elk Wilderness need to be aware of potential hazards associated with trees killed by mountain pine beetles. Photo by Bonnie Sinclair (Our Wander-Filled Life), used with permission.

Figure 6-4. Conceptual diagram of climate change effects on recreation. From Miller et al. (in press).

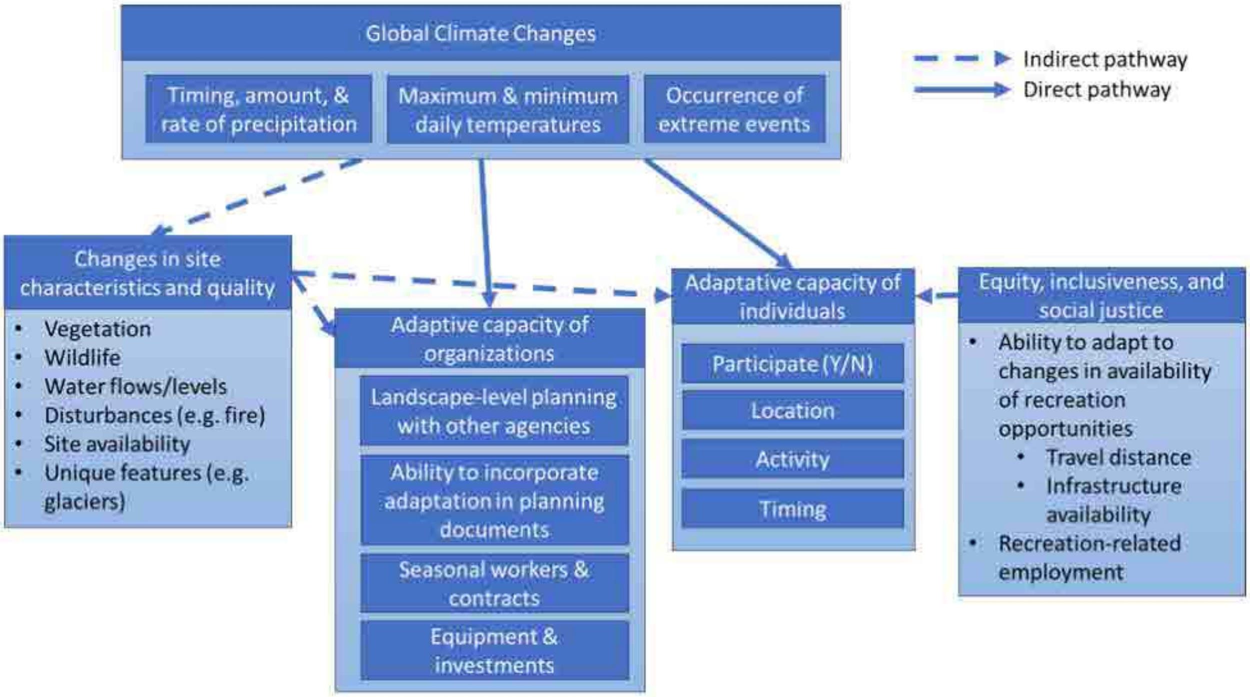

Figure 6-5. The Jasper Fire burned with mixed severity across 83,000 acres in the South Black Hills in summer, 2000. Image from Google Earth, posted at https://www.sdpb.org/blogs/news-and-information/forest-service-works-to-erase-the-jasper-fire-scar-in-black-hills.

Figure 6-6. Flooding projection map

Map is being prepared and will be included.

Figure 6-7. Projections for snow in the 2080s, showing decrease in snow residence time with respect to roads and trails in Black Hills NF (upper map), and decrease in April 1 snow-water equivalent (SWE) with respect to designated locations for winter recreation (lower maps).