Climate Change Vulnerability in the Black Hills National Forest (DRAFT)

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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 historical 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 annual temperature in the Black Hills region has risen around 2^{o}F.
- By mid-century, average annual maximum temperatures are projected to warm 4.3 to 5.3^{o}F compared to historical climate from 1961-1990. This future projection would be comparable to year 2012 with the hottest average annual maximum temperature, 62.4^{o}F, in the Black Hills ecoregions.
- By mid-century, average annual minimum temperatures are projected to increase by 4.1 to 5.2^{o}F compared to historical climate from 1961-1990. This warming would result in the average minimum temperature, historically at 31.7^{o}F in the Black Hills ecoregions, to rise several degrees above freezing by mid-century.
- No significant trends in historical precipitation have been observed, however precipitation for the Black Hills area is projected to increase slightly, primarily in winter and spring.
- The frequency of heavy rain events for the state of South Dakota has increased since 1990. The intensification and frequency of heavy rain events and associated flooding is likely to continue with the possibility of longer dry periods between events.
- The increase in evaporation rates due to rising temperatures may increase the rate of warm-season soil moisture loss and the intensity of naturally occurring droughts.

Hydrology and watersheds

- Warmer temperatures in winter and spring will reduce snowpack and the length of time snow persists.
- Climate change will likely increase the intensity of rainstorms and the potential for flooding in winter, spring, and early summer.
- Decreasing snowpack and shifts in precipitation patterns will increasing streamflow variability, with some high-flow years and some low-flow years.
- Changes in other disturbance processes, including wildfire and insect outbreaks, will 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, lower dry-season flows, increased flooding, and more variable summer stream flows, as well as indirect changes caused by expected increases in wildfire.

Vegetation

- Projected changes in climate will directly affect forest vegetation in the Black Hills by altering vegetation growth, vigor, mortality, and regeneration. Warmer temperatures, particularly during the summer, will increase drought stress. Increases in drought stress and decreases in snowpack will likely contribute to decreases in tree growth. These negative effects on tree growth will likely outweigh any positive effects on tree growth associated with a longer growing season and slight increases in precipitation projected to occur.

- Climate change will also have indirect effects on forest vegetation through changes in disturbance regimes and altered ecosystem processes. As temperatures increase, drought conditions will occur more frequently, and warmer and drier conditions will increase the likelihood of wildfire.
- 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 due to lack of seed sources and drought conditions. 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. Populations in the Black Hills of paper birch and white spruce are both located far south of the remainder of these species' respective ranges and may be especially vulnerable to warming.

Recreation

- Higher temperatures will extend the duration of the season favorable for warm-weather recreation (nature viewing, hiking, camping, etc.), increasing the number of people engaged in warm-weather activities, where 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 flow, which may impact angling success.
- Increased frequency and extent of wildfires and flooding will reduce access to recreational opportunities and damage recreation infrastructure, including roads located near streams.
- As snowpack declines in the future, there will be fewer opportunities for snow-based recreation (snowmobiling, cross-country skiing, downhill skiing), especially at lower elevations.

1. Introduction

Thomas J. Timberlake[1]

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 (NEPA). 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 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 with 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, which 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[2]

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 in the region. 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 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. The Northern Great Plains experiences frigid Arctic fronts from Canada that can bring extreme cold temperatures in winter affecting the Black Hills NF. While precipitation may come at any time during the year, warm moist air masses travel from the Gulf of Mexico up into the Plains in the spring, bringing most of the annual moisture.

The elevations of the Black Hills, ranging from 3,800-7,242 feet above sea level (Graham et al. 2019), 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, at higher elevations, the temperatures are cooler with more moisture. Storm and flood potential in the Black Hills is the lowest 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 greatest 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 ecoregion, which covers 89% of the Black Hills NF (Figure 2-1). The Foothills ecoregion surrounds the Limestone Plateau-Core Highlands, covering 10% of the Black Hills NF. The Shale Scablands, at the lowest elevation, surrounds the Foothills, and covers less than 1% of the Black Hills NF.

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

The climate of the Black Hills region is typed as a continental climate, with warm summers, cool winters, and precipitation mostly coming in the warmer months. Historical values for temperature and precipitation, annual or monthly averages, give an expectation of what the weather could be, while the variability give an indication of how hot or how dry the conditions have been historically. Climate data (1950-2013) for these three ecoregions are provided by Climate by Forest (U.S. Forest Service 2018) based on observations from weather stations within each ecoregion. While the average annual maximum temperatures[3] over the 64-year period are

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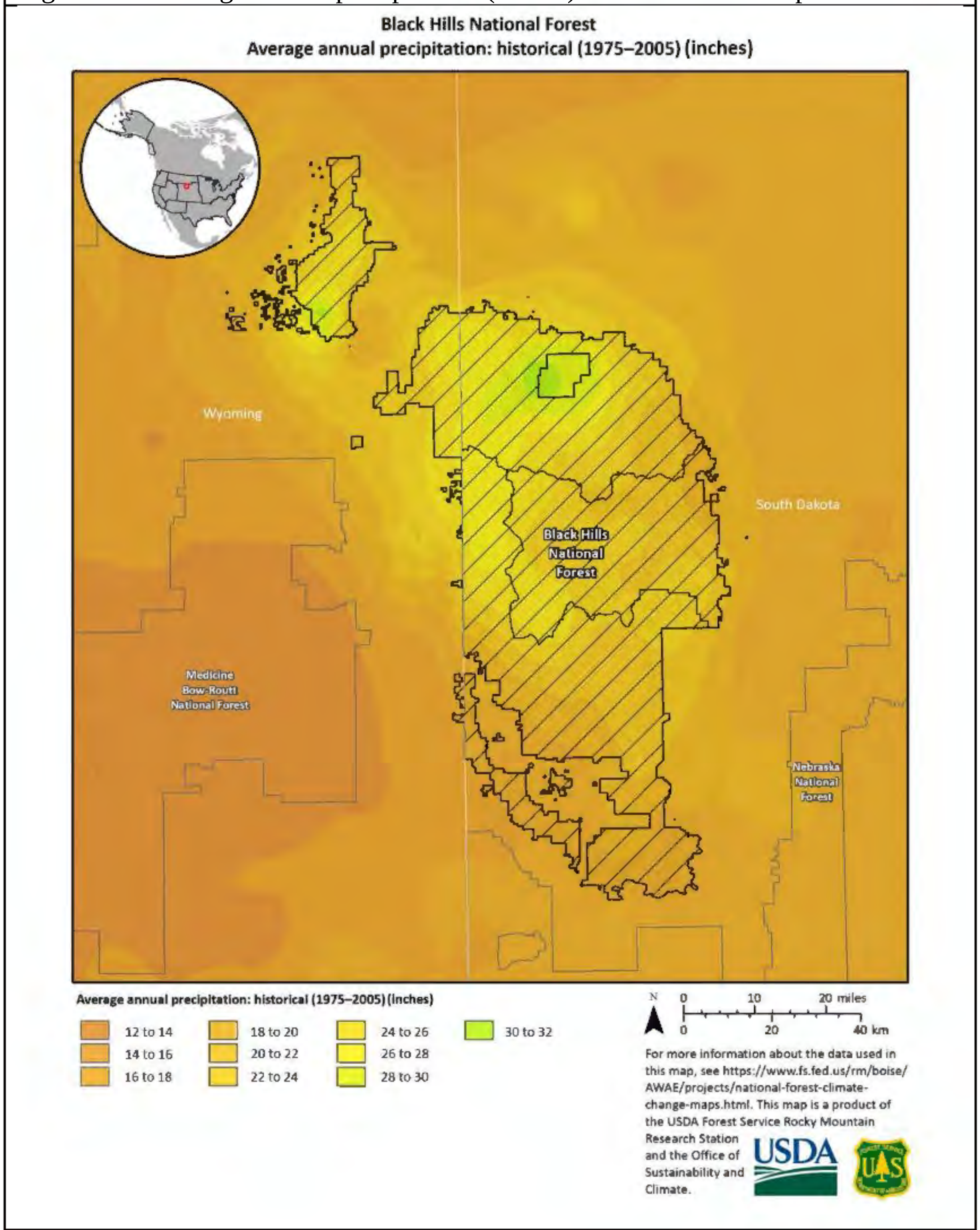
[3] Climate by Forest uses the term maximum/minimum daily temperature and in this report, the term 'average annual maximum/minimum temperature' is used. This report uses the same terminology for monthly data.

similar across the ecoregions (Table 2-1), Shale Scablands is the hottest ecoregion with the lowest annual precipitation (Figure 2-2). The Limestone Plateau-Core Highlands has the lowest average annual maximum temperature of 58.2°F, and the highest annual precipitation. Across all ecoregions, minimum temperatures for the 64-year period are just below freezing, ranging from 31.7°F to 31.9°F.

Figure 2-2. Average annual precipitation (inches) for the 1975-2005 period.



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

Though highly variable year to year, the annual values of temperature and precipitation for the three ecoregions track closely over the 64 years of the historical period (Figure 2-3), with Shale Scablands typically having the hottest average annual maximum temperature, 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 average minimum temperature each year, but not always. Over the historical period, the coldest average annual minimum temperature was reported in 1951 in all ecoregions, averaging around 28ºF (Figure 2-3). The lowest average annual maximum temperature was reported in 1993 when maximum temperatures were nearly 4 degrees lower than the 64-year historical average in each ecoregion.

Table 2-1. Historical annual averages and ranges for maximum temperature (ºF), minimum temperature (ºF) and total precipitation (inches) in the three ecoregions in the Black Hills NF over the 1950-2013 period. Source: U.S. Forest Service. 2018.

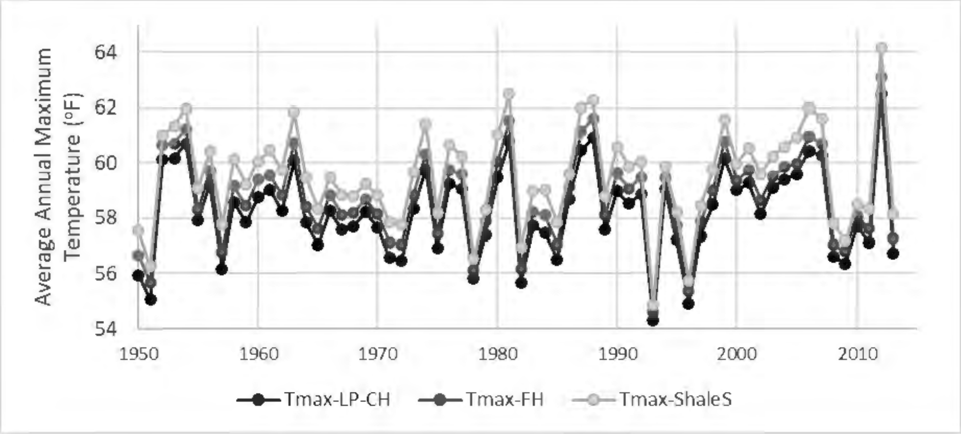
	Limestone Plateau-Core Highlands	Black Hills Foothills	Shale Scablands
Maximum Temperature	58.2ºF [54.3-62.5]	58.8ºF [54.6-63.1]	59.5ºF [54.9-64.1]
Minimum Temperature	31.7ºF [28.3-34.7]	31.7ºF [28.3-34.5]	31.9ºF [28.7-34.4]
Total Precipitation	18.4 inches [11.7 – 27.3]	17.3 inches [11.0-25.7]	16.3 inches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

Total annual precipitation ranged from 10 inches to 27 inches over the 1950-2013 period (Table 2-1, Figure 2-3). On average, the Limestone Plateau-Core Highland is the wettest ecoregion, with 18.4 inches of average annual 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 2-3). 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. The annual average snowfall across the state is 30 inches, however some areas in the Black Hills can get more than 70 inches of snow annually (Frankson et al. 2022).

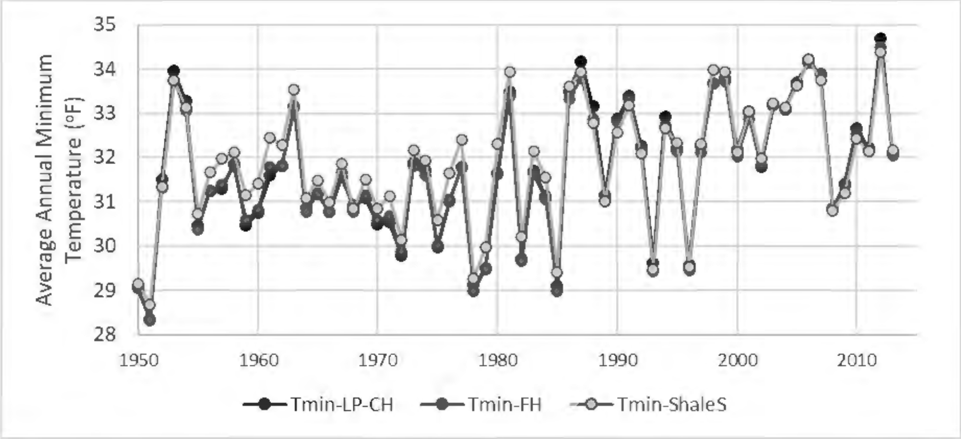
A critical aspect of reviewing historical climate is to set the historical climate in the context of the consequences to natural resources and ecosystem services. For example, the highest maximum temperature in the historical record occurred in 2012 in all three ecoregions: 64.1ºF in Shale Scablands, 63.1ºF Foothills, and 62.5ºF in the Limestone Plateau-Core Highlands. At the contiguous U.S. area, July 2012 was the hottest month recorded to that date in the instrumental record (Karl et al. 2012). Not only were the Black Hills hot, but the region was also in drought conditions. By September 2012, two-thirds of the contiguous U.S. was in drought with drought not breaking until 2014, a national-scale event that had not been seen in decades (Easterling et al. 2017). The year 2012 was the third driest year in the historical record in all three ecoregions (Figure 2-3). As hot temperatures and drought affected the Black Hills region, eleven fires were recorded in 2012, including the Oil Creek Fire, which burned 61,340 acres west of the national forest and was the second largest fire recorded up to 2012 in the Black Hills region (USFS 2012). As will be discussed in later sections, the frequency of these co-occurring climatic events (hot temperatures and drought) is likely to increase.

Figure 2-3. Historical average annual maximum temperature (°F) (a), average annual minimum temperature (°F) (b), and total precipitation (inches) (c) for three ecoregions in the Black Hills over the 1950-2013 period. Source data: U.S. Forest Service 2018. Limestone Plateau– Core Highlands: LP-CH, Black Hills Foothills: FH, and Shale Scablands: ShaleS

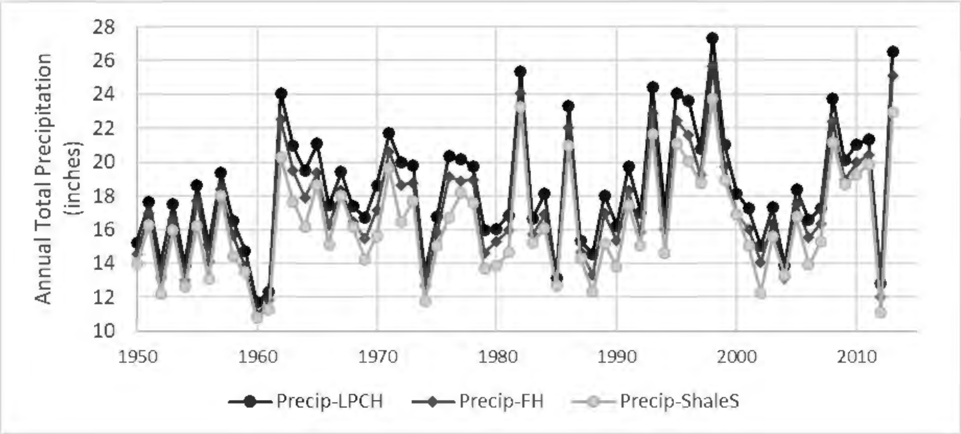
a) Maximum temperature



b) Minimum temperature



c) Total Precipitation



Seasonal climate

Consistent with a continental climate, average monthly temperatures in the Black Hills are coldest in January and February and warmest in July and August (Figure 2-4). Precipitation can occur in any month but is generally the greatest in May and June (NOAA 2021a). Flash-flood events have occurred from spring through fall, typically the result of slow-moving thunderstorms and rain-on-snow events (Driscoll et al. 2010). Additional information on extreme climate events is given in the next section.

Maximum temperatures in January and February average in the low 30s, with minimum temperatures around 10°F (Figure 2-4). Down-slope winds, such as chinook winds, can result in warming of winter temperatures (Abatzoglou et al. 2021), and have been linked to snowpack loss in the Dakotas (Hatchett et al. 2021). However, the most remarkable change in temperature occurred in the Black Hills on January 22, 1943, when the frontal boundary separating extremely cold Arctic air moving south from the warmer Pacific air moving west rolled along the northern and eastern slopes of the Black Hills. In Spearfish, temperatures rose from -4 to 45 °F, a rise of 49 degrees in two minutes, and then as the frontal boundary moved through, temperatures dropped back to -4°F (NOAA 2021b).

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 2021a). Monthly maximum temperatures range in the lower 40s for March and move into the 50s in April (Figure 2-4). 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 2021a).

Mild weather with thunderstorms characterizes May and June (NOAA 2021a). Maximum temperatures range from the high 60s in May to high 70s in June, with minimum temperatures ranging from the 40s to 50s (Figure 2-4). This time period comes when climate is transitioning from the two snowiest months (March-April) to two months with the most monthly precipitation, which typically occurs as rain (May-June). 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 2021c). 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 that nearly 15 inches of rain fell in about six 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 (Figure 2-4). 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 2021a). While Rapid City records an average of 9 thunderstorms days in August, with only 1.67 inches of rain (NOAA 2021a), intense thunderstorms can result in flooding. Near Hermosa, thunderstorms on August 17, 2007 resulted in 10.5 inches of rain, damaging homes and obstructing highways.

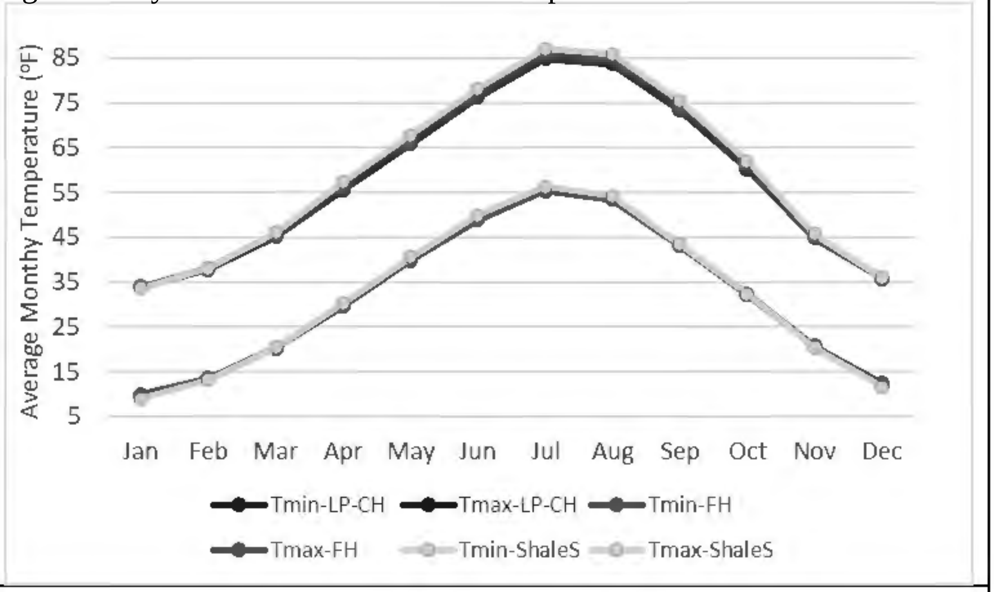
Mild weather with sunny days and cool nights characterizes September and October (NOAA 2021a). September highs are in the 70s for all ecoregions and lows are in the 40s, while October is cooler (Figure 2-4). The average first freeze in Rapid City is October 4 and late August through September in the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

October, although higher elevations sometimes receive snow in September (NOAA 2021a). On October 3-5 in 2013, the Black Hills and surrounding areas experienced an early season blizzard with high wind gusts (Frankson et al. 2022). Record snowfalls were reported: 55 inches over the 3-day period in Lead; and 23.1 inches in Rapid City, which is the second heaviest 3-day snowfall for the city (Frankson et al. 2022). Up to 45,000 livestock perished, with some owners losing more than 90% of their stock (Edwards et al. 2014). On October 11-17, 2013, heavy rain falling on melting snow from the October 3-5 blizzard resulted in flooding over the northern and central Black Hills. Flows in Battle Creek were estimated at 1300 cubic feet per second (cfs) compared to normal flows during October of less than 5 cfs (NOAA 2021c).

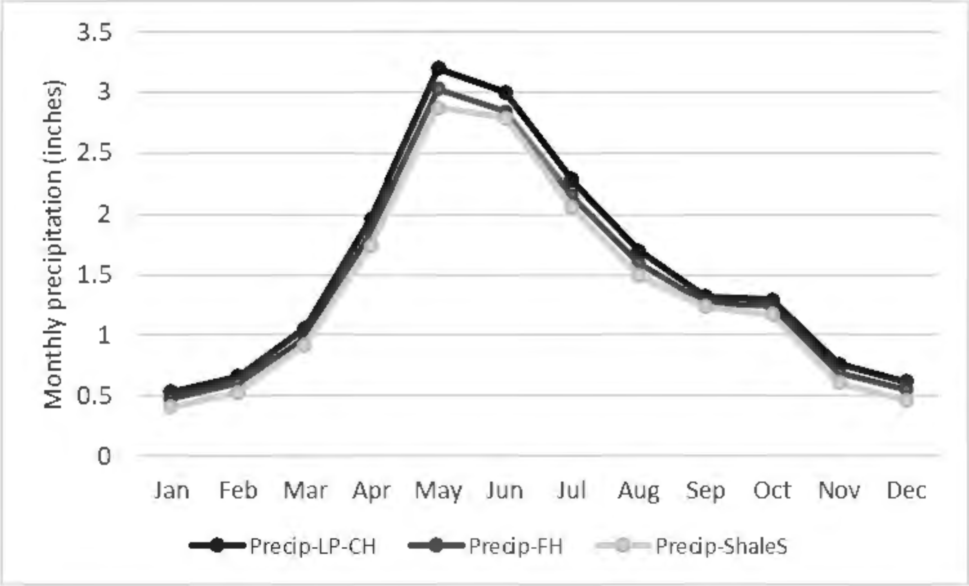
Cold temperatures return in November and December. Maximum temperatures drop below 50^{o}F in November and by December are well into the 30s (Figure 2-4). Mean minimum temperatures are below freezing in both months and can drop below zero (NOAA 2021a). Arctic fronts from Canada bring below-zero temperatures for short periods of time (NOAA 2021b,c). Snowfall averages about 5 inches in November, and in December only two days typically receive more than 1 inch of snow (NOAA 2021a).

Figure 2-4. Historical average monthly maximum and minimum temperatures (^{o}F) (a) and monthly total precipitation (inches) (b) for the three ecoregions of the Black Hills over the 1950-2013 period. Source data: Climate by Forest (U.S. Forest Service 2018). Limestone Plateau-Core Highlands: LP-CH, Black Hills Foothills: FH, and Shale Scablands: ShaleS

a) Average monthly maximum and minimum temperatures



b) Monthly precipitation



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 larger region in which the Black Hills NF is located. These studies may focus on different time periods and slightly different regions. Trends in temperature can be studied as 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, blizzards, extreme cold or hot, and 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. 2022). Average temperature warming in South Dakota was concentrated during winter and spring. Nighttime minimum temperatures in South Dakota have increased about twice as much as daytime maximums since the early 20th century (Frankson et al. 2022).

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. 2022). 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).

The Black Hills area has experienced blizzards from early fall to late spring (National Weather Service undated-1). Coleman and Schwartz (2017) define blizzards as extreme winter storms with strong winds and falling or blowing snow with reduced visibility for an extended period. In their analysis, eastern South Dakota typically experienced more November blizzards in contrast with western South Dakota, where blizzards were more common in April (Coleman and Schwartz 2017). Frankson et al. (2022) reported the probability of a blizzard occurring anywhere in the state of South Dakota in any given year was 50%. They also concluded that South Dakota's northern location and proximity to the typical U.S. winter storm track make it highly susceptible to heavy snows, high winds, and low wind-chill temperatures.

Recent analyses of extreme precipitation indicate 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 2021). For South Dakota, the number of 2-inch rain events have increased 22% since 1990, when compared to the long-term (1900-2020) average (Frankson et al. 2022). Over the central U.S., 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 rainfall intensity, it may also be associated with longer dry spells between extreme events (Dai et al. 2017, 2020).

Tornadoes are a historical component of Black Hills weather (National Weather Service undated-2). No analysis of historical trends is available for the Black Hills region. Many studies have cautioned that the reporting of tornadoes, particularly over a long period of time, can be influenced by population shifts, greater public awareness, increased number of storm chasers, and recent improvements in identifying tornadoes with radar (Moore et al. 2021). A historical analysis of tornadoes across South Dakota suggested possible cyclical patterns in tornadoes over time, and an influence of ocean temperatures and sea pressures (North Atlantic Oscillation and Atlantic Multi-decadal oscillation) on annual tornado patterns (Nouri et al 2021). At the scale of the United States, a decrease in the number of days per year with tornadoes and an increase in the number of tornadoes on these days has been reported (Kossin et al. 2017). Because tornadoes are influenced by regional and local weather patterns as well as topography, there is large uncertainty in how climate change will affect these patterns (see Future Extreme Events section).

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 Creek 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.

Projections of Future Climate

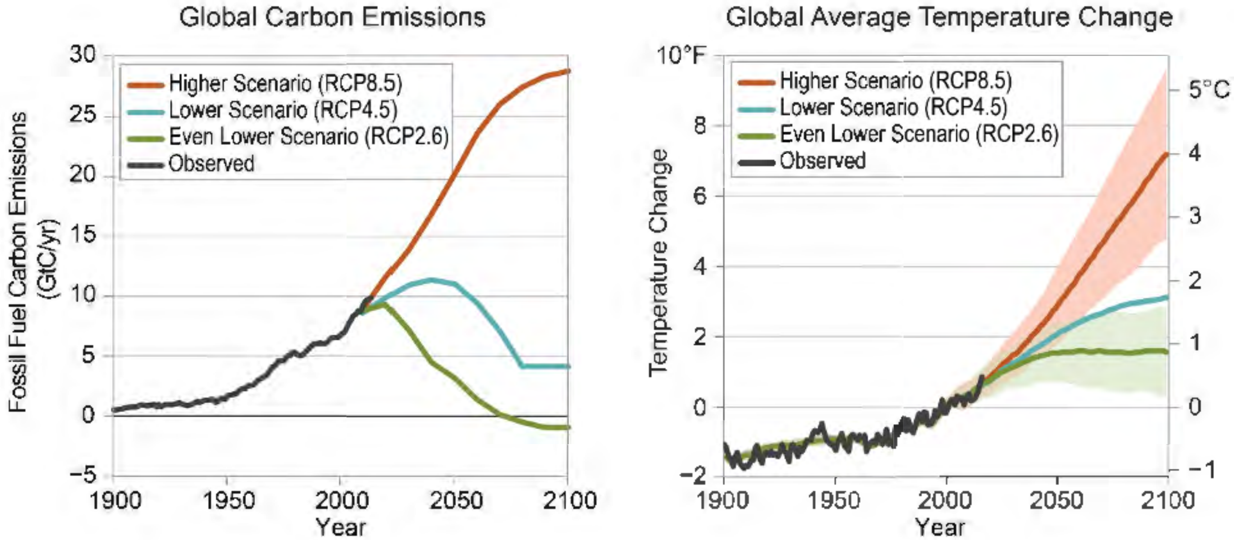
Future projections of climate provide an opportunity to consider what these plausible futures might mean to natural resources and ecosystem services. We draw from the climate projections that were used in the most recent National Climate Assessment (Wuebbles et al. 2017). In that assessment, 32 projections (from global climate models) 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 the models project historical climate) and the interdependency of models (how similar the model structure and parameterization are between the models) (Sanderson and Wehner 2017).

Scenarios were developed to create a plausible future based on different assumptions about human choices, land use changes, and concentrations and emissions of different greenhouse gases. These scenarios are called Representative Concentration Pathways (RCPs) (Hayhoe et al. 2017, 2018). Humans have contributed greenhouse gases to the atmosphere since pre-industrial times, and those contributions are quantified in terms of how much more heat (radiative forcing) is in the atmosphere relative to pre-industrial times. The current atmosphere has a radiative forcing of about 2 watts per square meter more than pre-industrial times. 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/m^2) more than pre-industrial times, what types of emissions would characterize this forcing, and then what would happen to the global climate if the atmosphere held this amount of radiative forcing. The medium forcing (RCP 4.5) and the highest forcing (RCP 8.5) are the scenarios used to project future climate in this analysis.

RCP 8.5 represents a high emissions scenario where there is a continual increase to the year 2100 in greenhouse gas emissions from fossil fuel combustion and emissions of carbon dioxide and other heat-trapping gases from human activities, including land use and land-use change (Figure 2-5). This scenario assumes no policy constraints on emissions. By 2100, the increase in global temperature is projected to be between 4.2 and 8.5°F, shown by the burnt orange shaded area relative to the 1985-2015 average. Current atmospheric carbon dioxide levels are around 400 parts per million (ppm), and by 2100, the levels for the RCP 8.5 scenario would be over 900 ppm. While this scenario is thought of as a "worst-case scenario", Schwalm et al. (2020) reported that the RCP 8.5 emissions are in close agreement with historical total cumulative carbon dioxide emissions, and this scenario represents emissions until mid-century under current and stated policies.

RCP 4.5 represents a lower emissions scenario and assumes policies limit greenhouse gas emissions such that there is a stabilization in radiative forcing. Emissions peak at mid-century and then decrease. Emissions are flat at the end of century. Under RCP 4.5, the increase in global average temperature is projected to be 1.7–4.4°F (range not shown on graph) relative to 1986–2015. This scenario corresponds to atmospheric carbon dioxide levels of around 550 ppm by 2100 (Hayhoe et al. 2017).

Figure 2-5. Observed and projected changes in global average temperature (right) depend on observed and projected emissions of carbon dioxide from fossil fuel combustion (left) and emissions of carbon dioxide and other heat-trapping gases from other human activities, including land use and land-use change. Thick lines within shaded areas represent the average of multiple climate models. The shaded ranges illustrate the 5% to 95% confidence intervals for the respective projections. In all RCP scenarios, carbon emissions from land use and land-use change amount to less than 1 gigaton carbon by 2020 and fall thereafter. Source: Hayhoe et al. 2018 (adapted from Wuebbles et al. 2017)



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. Forest Service 2018). The projections are summarized to the average value across all 32 projections for 20 climate variables, and to the monthly values for 3 climate variables. The data available include historical observations (used in the previous section), modeled historical projections, and future projections at annual and monthly time periods.

Statistical analysis conducted for Climate by Forest 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 a climate variable in a 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 NF.

Future annual average maximum and minimum temperature

The projected mid-century increase in maximum temperatures under the moderate RCP 4.5 scenario for the Limestone Plateau and Core Highlights area would result in an average annual maximum temperature nearly the same as the 2012 maximum temperature of 62.4 ^{o}F, the hottest observed temperature over the 1950-2013 period (Table 2-2, Figure 2-6). Average annual maximum temperature under RCP 8.5 increases continually to historically unprecedented maximum temperatures at end of the century. These future projections in maximum temperature are statistically significant from the historical climate of 1961-1990, and the confidence intervals are small relative to the change in temperature (Table 2-2).

The average number of days with maximum temperature over 95^{o}F is projected to triple by mid-century – increasing from the historical average of 7 days to projected mid-century average of 23 days under RCP 4.5 and 28 days under RCP 8.5 (Table 2-2). Over the 1950-2013 period, the year with the most days above 95^{o}F occurred in 1988 with 17.4 days, and the average annual maximum temperature was 60.9^{o}F (2.7^{o}F above the 64-year mean) (Figure 2-3).

By mid-century, the average annual minimum temperature is projected to be above freezing, 35.5^{o}F under the moderate RCP 4.5 scenario, and 36.6^{o}F under the RCP 8.5 scenario (Table 2-2, Figure 2-7). Over the 64-year historical period, the observed annual minimum temperature ranged from a low of 28.3^{o}F to a high of 34.7^{o}F in 2016. The minimum temperature was at or above 32^{o}F for a total of 26 times in the 64-year period, with nearly all of these above-freezing temperatures (25 times) occurring since 1980 (Figure 2-3). This pattern in above-freezing temperatures is consistent with the Frankson et al. (2022) observation that for South Dakota, winter warming since 2000 is reflected in a below-average number of very cold days, rather than increased average or maximum temperatures. By the end of the century, the annual minimum temperature is projected to increase to historically unprecedented temperatures several degrees above freezing, 36.7^{o}F under RCP 4.5 and 41.9^{o}F under RCP 8.5 (Figure 2-7). Icing days, defined as days when maximum temperature is below 32^{o}F, are projected to decrease from the historical average of 42.2 days to 32.5 days under RCP 4.5 and 30.7 days under RCP 8.5 at mid-century (Table 2-2). Over the 1950-2013 period, days with maximum temperature below freezing varied greatly and ranged from 20 days to 75 days in a year (Figure 2-7).

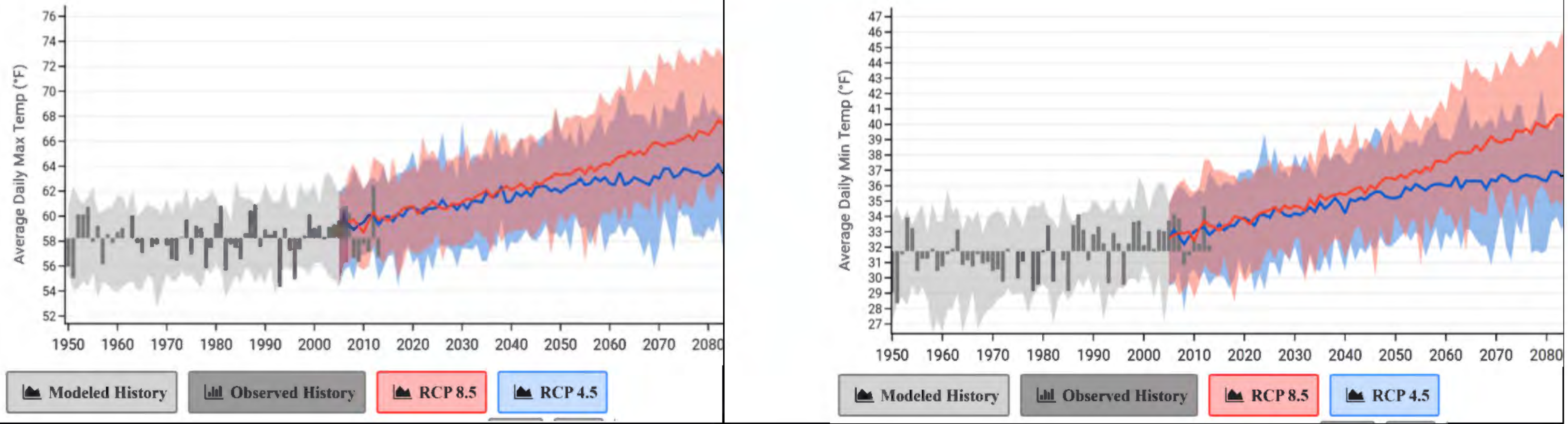
Table 2-2. Projected change in average annual maximum and minimum temperature, number of days the maximum temperature was/is projected to be above 95ºF, and number of days the maximum temperature was/is projected to be below 32ºF for the period 2036-2065 compared to the 1961-1990 baseline period under 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. Forest Service (2018)

Variable	1961-1990 Mean	Scenario	Mean change by 2036-2065 (confidence interval)
Average Annual Maximum Temperature (ºF)			
	58	RCP 4.5	4.3 (+/- 0.28)
		RCP 8.5	5.3 (+/- 0.41)
Average Annual Minimum Temperature (ºF)			
	31.4	RCP 4.5	4.1 (+/- 0.11)
		RCP 8.5	5.2 (+/- 0.39)
Average Days per Year Maximum Temperature above 95ºF (days)			
	6.1	RCP 4.5	16.1 (+/- 1.0)
		RCP 8.5	21.9 (+/- 1.9)
Average Days per Year Maximum Temperature below 32ºF (icing days)			
	43.5	RCP 4.5	-11 (+/- 1.3)
		RCP 8.5	-12.8 (+/- 1.2)

Figure 2-6. 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. The blue band shows the range of the 32 projections for a possible future in which global emissions of heat-trapping gases peak around 2040 and then become stable. The red band shows the range of the 32 projections under RCP 8.5, a potential future in which global emissions of heat-trapping gases continue to increase through 2100. Source: U.S. Forest Service (2018).

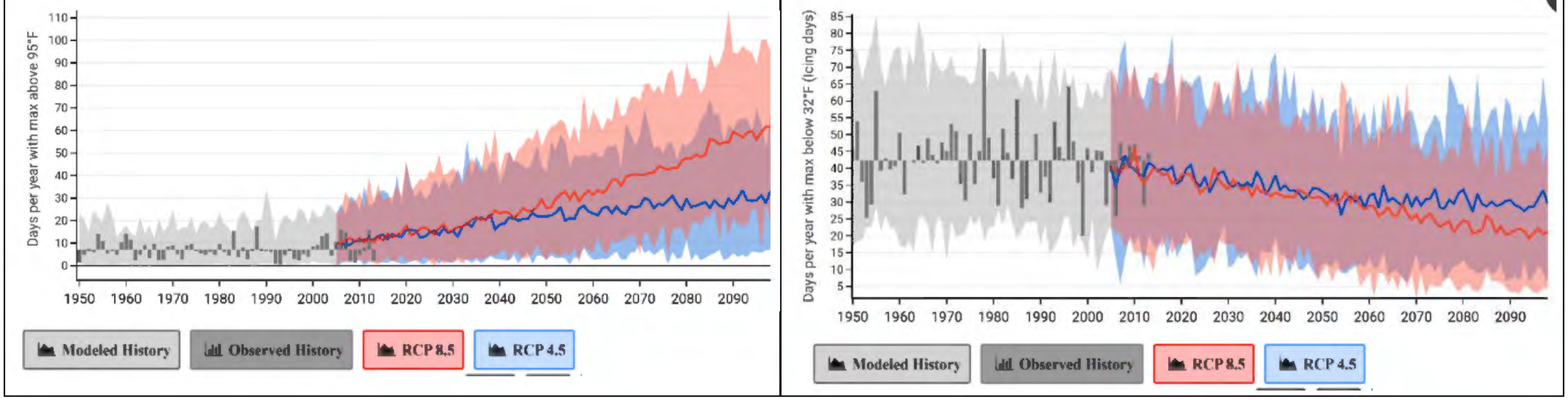
A. Average Daily Maximum Temperature (°F)

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 precipitation

Total annual precipitation is projected to increase by 0.6 inches under both future climate scenarios by mid-century (Table 2-3). This projected change is small relative to the annual historical average of 18.2 inches (1961-1990 period) and small relative to the historical variability over the 1950-2013 period (Figure 2-7). Further, an indication of the large uncertainty associated with precipitation projections is that the confidence intervals under both scenarios are large, nearly 50% of the projected change (Table 2-3).

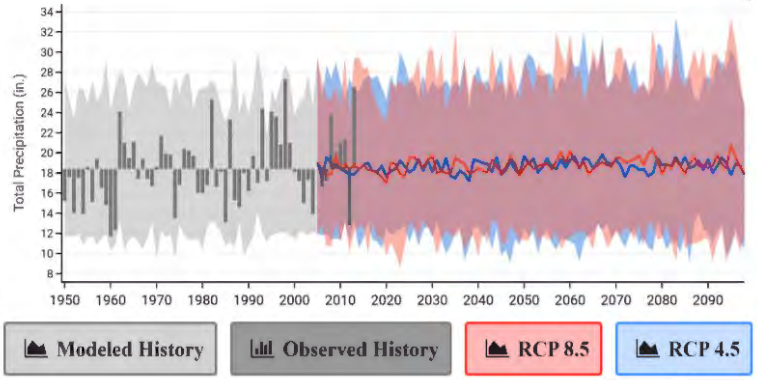
Dry days are the number of days per year when precipitation is less than 0.01 inch. Historically, the average number of dry days was 224.6 days per year and ranged from 189 days in 1982 to 265 days in 1952 (Figure 2-7). Dry days are projected to increase on average by 1.3 days under RCP 4.5, with a maximum projection of 1.7 additional dry days under RCP 8.5 (Table 2-3). Though the projected change is statistically significant, uncertainty in the projections is high given the large confidence intervals.

Table 2-3. Projected change in annual precipitation (inches) in the period 2036-2065 compared to 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, unless noted as not significant (NS). Source: U.S. Forest Service. (2018).

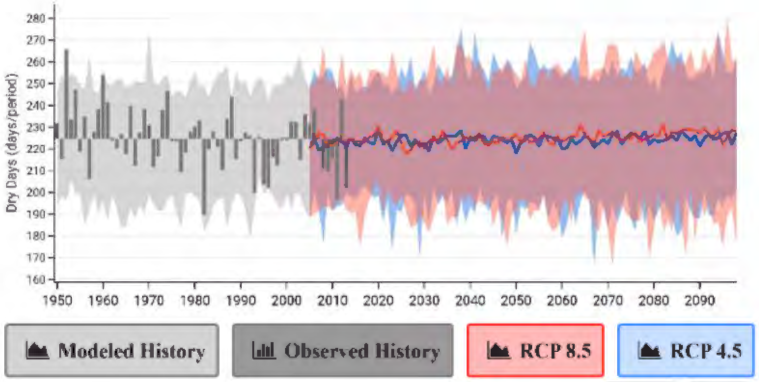
Variable	1961-1990 mean	Scenario	Mean change by 2036-2065 (confidence interval)
Total annual precipitation (inches)			
	18.2	RCP 4.5	0.6 (+/-0.35)
		RCP 8.5	0.6 (+/- 0.33)
Dry days (number of days)			
	222.8	RCP 4.5	1.3 (+-1.25)
		RCP 8.5	1.7 (+/- 1.20)

Figure 2-7. 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. The blue band shows the range of the 32 projections for a possible future in which global emissions of heat-trapping gases peak around 2040 and then become stable. The red band shows the range of the 32 projections under RCP 8.5, a potential future in which global emissions of heat-trapping gases continue increasing through 2100. Source: U.S. Forest Service. (2018).

A. Total annual precipitation (inches)



B. Number of Dry Days (days)



<ins>Monthly projections</ins>

By mid-century, monthly maximum temperatures are projected to rise each month between 3°F (April) and 5.7°F (August) above the 1961-1990 averages (Figure 2-8). Historically maximum temperatures were above freezing in the winter months by 1 or 2°F; by mid-century, winter temperatures will be a minimum of 5°F above freezing. The largest increases in maximum temperature occur in the summer months of July and August, with monthly averages projected to be nearly 90°F for August by mid-century (Figure 2-8). Differences between the two scenarios (RCP 4.5 and 8.5) are small at mid-century; however, by the end of the century, monthly RCP 8.5 projections are a minimum of 5°F greater than projections under RCP 4.5. By the end of the century, projected maximum temperatures for July and August are close to 95°F.

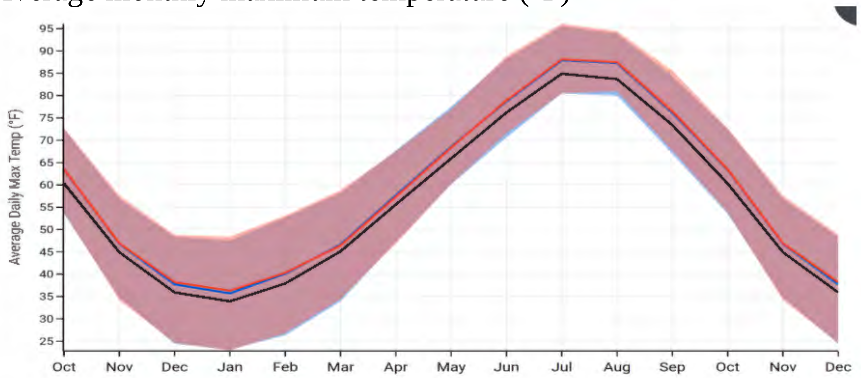
By mid-century, monthly minimum temperatures are projected to rise each month between 2.8°F (April) and 4.6°F (August) above the 1961-1990 averages (Figure 2-8). The average minimum temperature for the month of April, historically below freezing, is projected to be above freezing at mid-century; similarly, the month of October, historically just above freezing (32.4°F), is projected to be several degrees above freezing at 35.8°F by mid-century. While average minimum temperatures for the months between November and March remain below freezing in the projections, temperatures are projected to rise several degrees in each month (Figure 2-8). These temperature increases in the spring and fall transition periods, as well as in the winter months, have implications for the winter snow season (see Chapter 3).

Mid-century projections under RCP 4.5 for monthly precipitation indicate increases of 0.1 inch in the months of January, March, June, September, and November, and an increase of 0.3 inch in April (Figure 2-8). Decreases are projected for July (0.1 inch), August (0.4 inch), and October (0.2 inch). The monthly precipitation projections for RCP 4.5 and 8.5 are similar, with slightly larger increases under RCP 8.5. Frankson et al. (2022) concluded that winter precipitation is projected to increase in the Black Hills region (Figure 2-9, see Chapter 3 also).

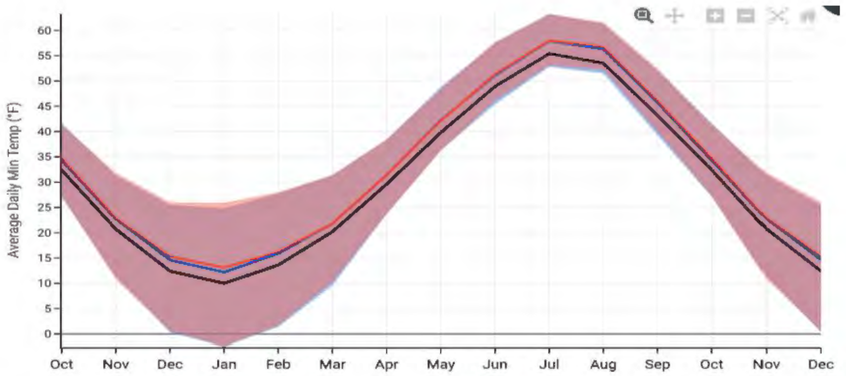
Monthly temperature and precipitation values have greater historical variability than annual climate data. Consequently, these future monthly projections have more uncertainty than annual projections. No statistical analysis for change under RCP 4.5 or RCP 8.5 is provided by Climate by Forest.

Figure 2-8. Historical observations and future projections for monthly average maximum temperature, monthly average 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; projections are for the 2036-2060 period. The blue band (RCP 4.5) shows the range of the 32 projections for a possible future in which global emissions of heat-trapping gases peak around 2040 and then become stable. The red band (RCP 8.5) shows the range of the 32 projections for a potential future in which global emissions of heat-trapping gases continue increasing through 2100. Source: U.S. Forest Service. (2018).

A. Average monthly maximum temperature (°F)



B. Average monthly minimum temperature (°F)



C. Total precipitation

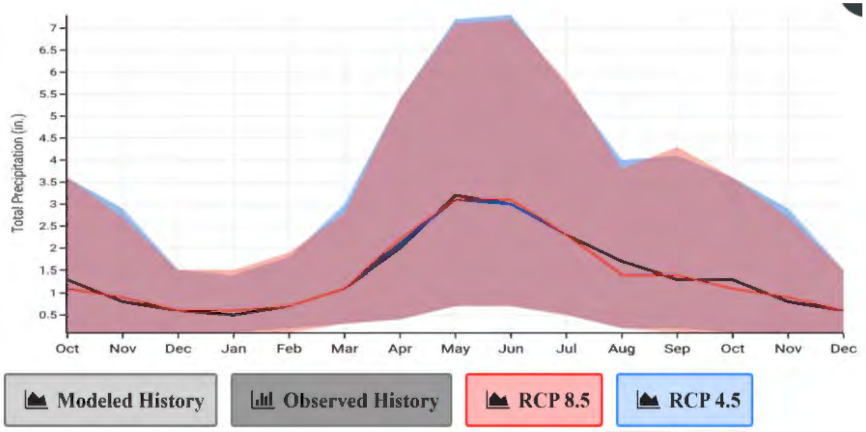
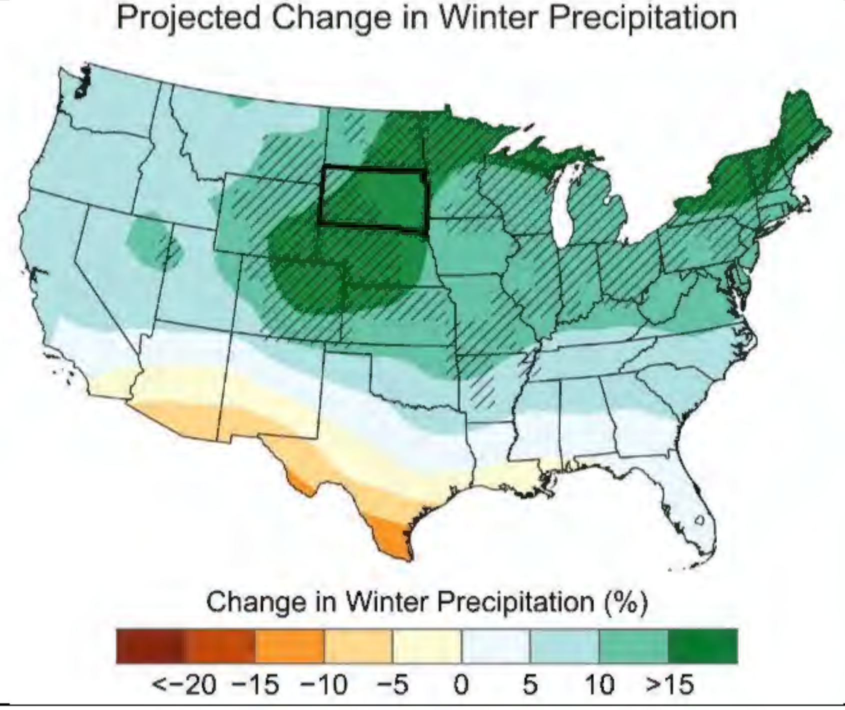


Figure 2-9. Projected changes in winter precipitation (%) for the middle of the 21st century compared to the late 20th century under RCP 8.5. Hatching represents areas where the majority of climate models indicate a statistically significant change. Winter precipitation is projected to increase by 10–20%. 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. 2022)



Future Extreme Events

Extreme climatic events, such as extreme storms, tornadoes and other wind events, and drought have occurred historically in the Black Hills and are likely to continue to occur. However, projecting these events at fine spatial scales under a changing climate is challenging. Consequently, a large uncertainty exists in our understanding of future climatic events.

Studies suggest that extreme storm events may increase in the future. In the review of historical climate above, it was noted that heavy rain events in South Dakota and the Missouri River Basin have become more frequent since 1990 (see Trends in historical climate and extreme events). Feng et al. (2016) showed this shift was related to changes in mesoscale convective systems, the largest type of convective storms, in the central United States. Climate models generally project an increased intensification and frequency of extreme storms. Dai et al. (2020) describe the process by which the size of intense storms increases while their number decreases, with each rainstorm event removing more moisture from the air, such that the next storm takes longer to form. Thus, while future storms may intensify, there may be longer dry spells between the extreme storms. Frankson et al. (2022) conclude that extreme precipitation events in South Dakota are projected to increase in frequency and intensity, raising the risk of springtime flooding. The Climate Change Science Report for the Fourth National Climate Assessment assigned a medium confidence to the likelihood of future extreme storms in the United States (Wuebbles et al. 2017).

The historical review of tornadoes did not identify a shift in the dynamics of tornadoes in the Black Hills region (see Trends in historical climate and extreme events). Studies done at larger spatial scales suggest that the lower energy tornadoes have increased while the higher energy tornadoes have decreased in number (Kossin et al. 2017). The variability and the influence of regional and local process on these events are such that projecting these events under climate change is challenging. The Climate Change Science Report for the Fourth National Climate Assessment concluded that that climate projections contain the types of changes that would support an increase in the frequency and intensity of severe thunderstorms (tornadoes, hail, winds). However, confidence in the details of where those events might occur is low (Wuebbles et al. 2017).

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 to 2014. Precipitation decreases are projected for July and August, the same months that temperatures will increase. These conditions are such that drought is likely to occur under future climate change. Frankson et al. (2022) conclude that increases in evaporation rates due to rising temperatures may increase the rate of soil moisture loss and the intensity of naturally occurring droughts. The uncertainty as to where drought will likely occur is high. In a study exploring the likelihood of three different extreme events in wildlife refuges across the United States, Martinuzzi et al. (2016) reported that extreme heat was projected for all refuges, but the wildlife refuges in the Mountain Prairie region, which includes the Black Hills, did not see a projected increase in drought.

The Black Hills has experienced a number of extreme events where more than one event was coincident with another event. 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).

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 range 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 (e.g., ponderosa pine forests and a 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. The projections summarized in this chapter identify overall trends, but the actual changes in climate in specific places will vary with features like topography. The experiential knowledge of local land managers will be important in interpreting the likely future projections and consequences of shifts in temperature, precipitation, rainfall intensity, dry days, and the growing season.

Maximum and minimum temperatures are projected to rise over the next 50 years by more than they have changed over the last 100 years. Average minimum temperatures may be above freezing by mid-century, a potentially significant change. Maximum temperatures will be hot; the number of days each year above 95^{o}F is likely to increase from 7 days to 23 days per year, a historically unprecedented occurrence. While the northern Great Plains are projected to see increased precipitation, the precipitation projections for the Black Hills indicate a small increase in annual precipitation, with increases more likely in winter and spring. Precipitation projections have much more uncertainty than temperature projections, particularly for small, expected changes and where regional and local characteristics influence precipitation dynamics. It is likely that the Black Hills will see increased intensity and frequency of heavy rainfall events and associated flooding, which also have consequences for hydrology and soils. 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 those during the hot and dry year of 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 NF.

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3. Hydrology and watersheds

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Introduction

Effects on water will be a major determinant of how climate change impacts ecosystems. In the Black Hills region, warmer temperatures will reduce snowpack and the length of time that snow persists, particularly at lower and mid-elevations. Climate change may increase the intensity of rainstorms and the potential for flooding in spring and early summer. These effects will contribute to increased variability in streamflow, both within years and among years. In the future, there may be both high-flow years and low-flow years. Changes in disturbance processes, including wildfire and insect outbreaks, will affect runoff and potential for mass wasting. These climate change effects on hydrology are discussed in more detail in the sections below.

Snowpack

Declines in snowpack, 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 landscapes 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 below freezing 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 (see historical SWE in the Black Hills in Figure 3-1), 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 (NF), ranging from a complete loss in the lower and mid-elevations to significant declines in SWE and SRT at higher elevations (Figures 3-2 and 3-3). 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 (28 to 37 days) relative to current SRT by 2080 (Figure 3-3). Current SRT ranges from 35 to 80 days, depending on location and elevation. These projected decreases correspond to a nearly complete loss of persistent snowpack at low elevations and a loss of one-third to a half of

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SRT at higher elevations. Declines in snowpack may be most impactful in mid-elevation areas that currently maintain a persistent snowpack but have average temperatures near freezing.

Changes in Precipitation and Flooding

Precipitation drives 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 NF, the projected trend is an increase in precipitation, with significant increases in winter and spring (see Chapter 2). 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 Basin suggest that streamflow has increased in the 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 statistically significant increasing trend in streamflow, 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 and, in turn, more water flows into streams rather than being evaporated (e.g., Dai et al 2020). Historical analyses based on weather stations do not indicate clear trends in total annual precipitation (see Chapter 2).

The Variable Infiltration Capacity (VIC) hydrologic model (driven by five different global climate models) was used to project future stream flow and flood risk for the Black Hills NF (Liang et al. 1994; Wenger et al. 2010). Projections used RCP 8.5 and were summarized for an end-of-century time period centered on 2080 (2071-2090). The model projections suggest that stream flows and the 1.5-year flood magnitude is likely to increase across all streams in the forest, particularly in areas in the northern Black Hills where larger decreases in snowpack are expected (Figures 3-4 and 3-5). 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 3-6).

Precipitation intensity also affects flood risk. One consequential outcome of a warming atmosphere is that when precipitation occurs, the same total volume of precipitation is expected to fall with greater intensity over a shorter duration, 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. 2022). 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).

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 3-7). The primary mechanism expected to drive lower summer flows is reduced snowpack in winter (Figures 3-2 and 3-3), leading to earlier runoff (Figure 3-8) 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 will likely be moderated in parts of the region where groundwater flow dominates contributions 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

As discussed in the chapter on vegetation, a warmer climate is expected to lead to more frequent and severe droughts, and these drought conditions and lower snowpack will increase the likelihood of wildfire. These changes in disturbance regimes will affect hydrologic and geomorphic responses in watersheds (e.g., Goode et al. 2012; Thompson et al. 2013). 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).

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 Tarboton 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 in other areas 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).

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). 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 that survive in undisturbed areas can recolonize disturbed areas over time.

Studies from other parts of the western United States suggest that 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 relative to solar insolation, surrounding landforms, groundwater contributions, and canopy removal. 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°F warmer (Dunham et al. 2007). Increased radiation accounted for 50% 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) 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 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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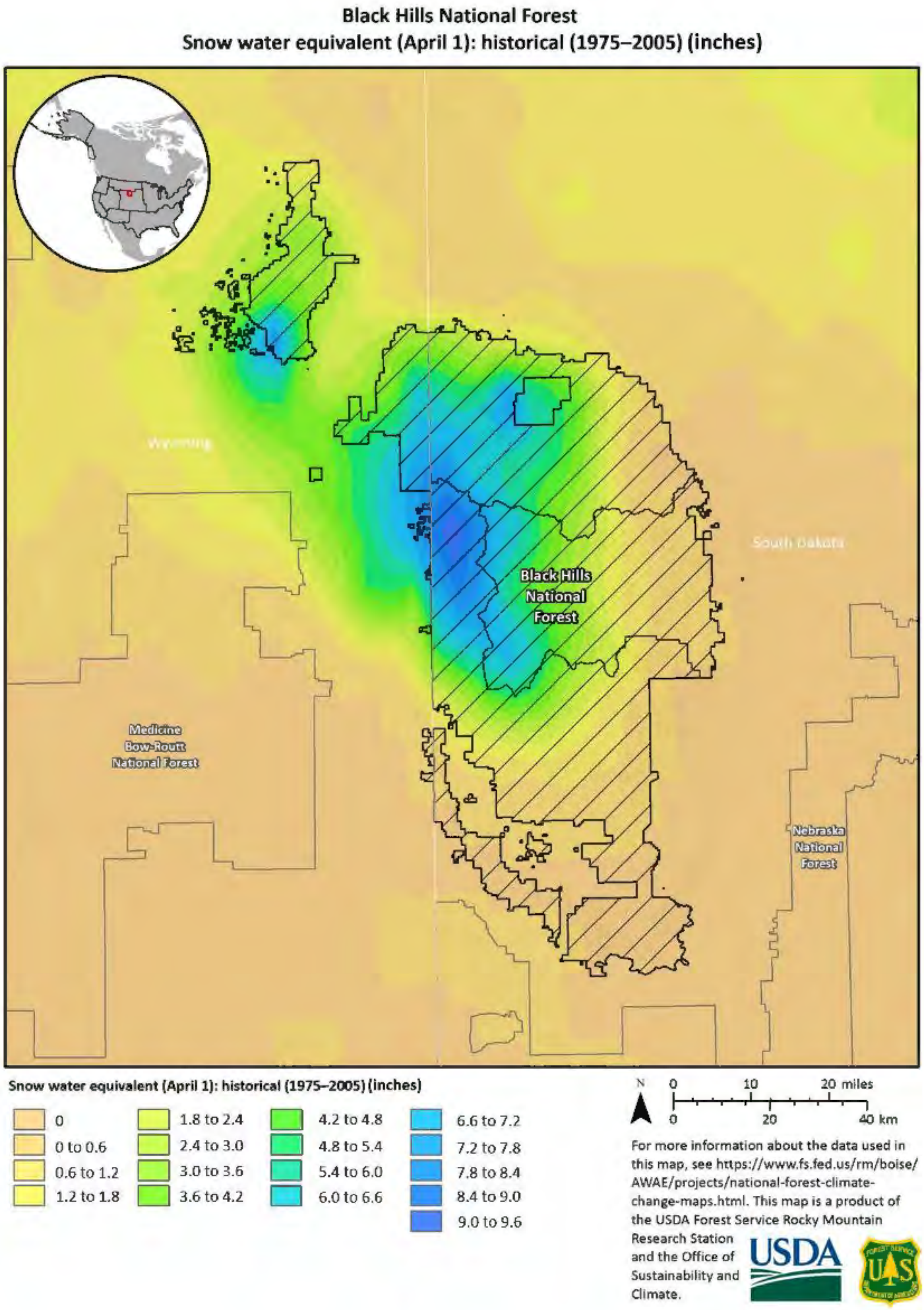


For more information about the data used in this map, see https://www.fs.fed.us/rm/boise/AWAE/projects/national-forest-climate-change-maps.html. This map is a product of the USDA Forest Service Rocky Mountain Research Station and the Office of Sustainability and Climate.

Figure 3-1. Average snow water equivalent in the Black Hills region from 1975-2005. Data and methods description are available at the National Forest Climate Change Maps webpage.

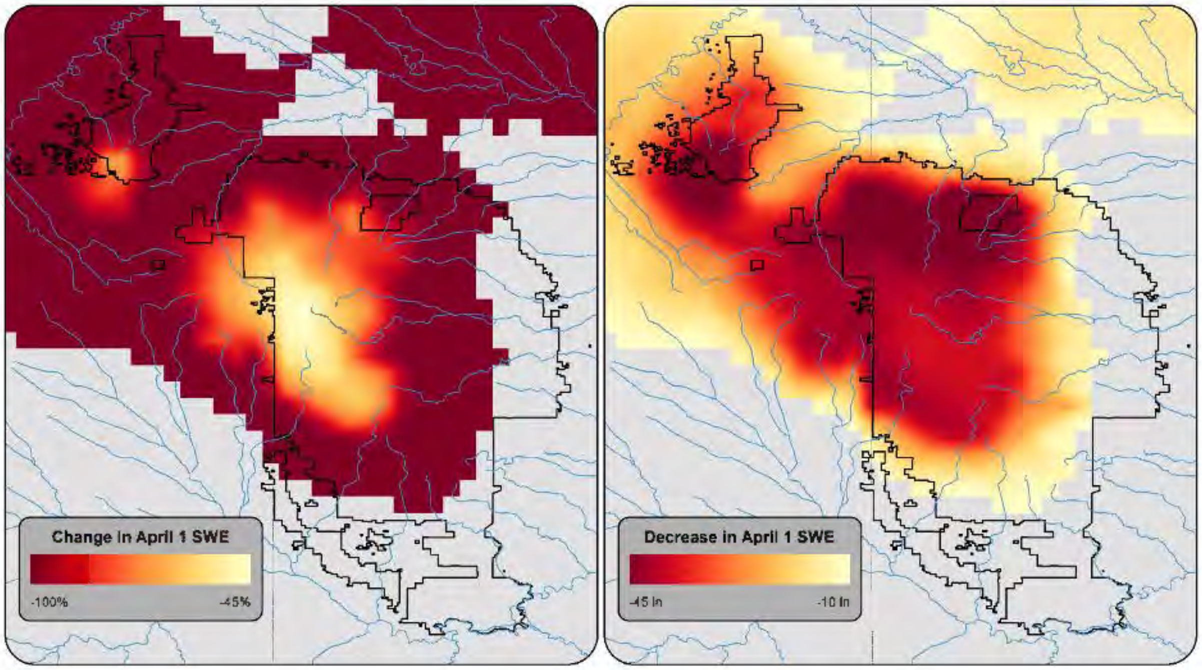


Figure 3-2. Projected changes in April 1st snow-water equivalent (SWE) in the Black Hills National Forest region from historical conditions (1975–2005) to the 2080's (2071–2090) based on temperature increases projected from a 20 global climate model ensemble mean under RCP 8.5. Data and methods description are available at the National Forest Climate Change Maps webpage. Figure by R. Norheim.

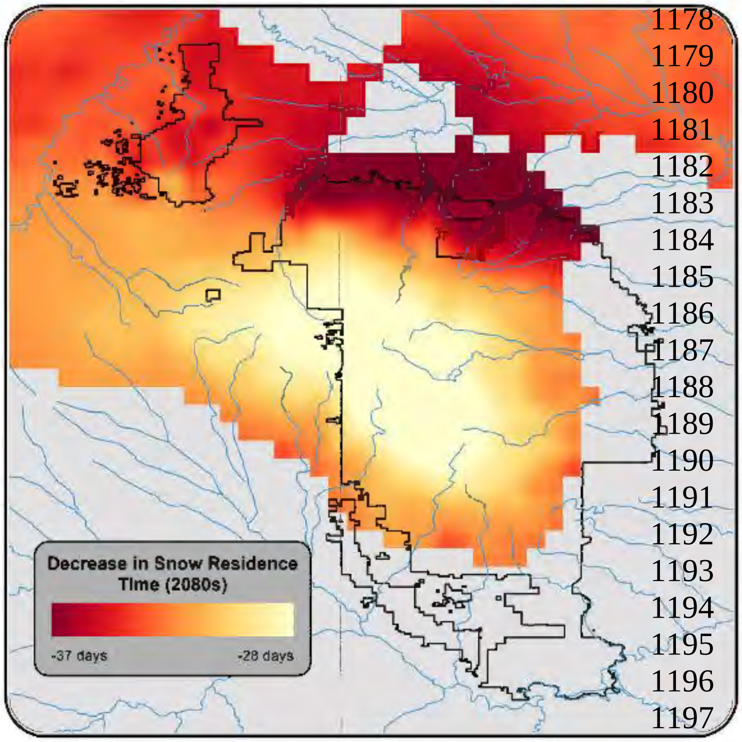
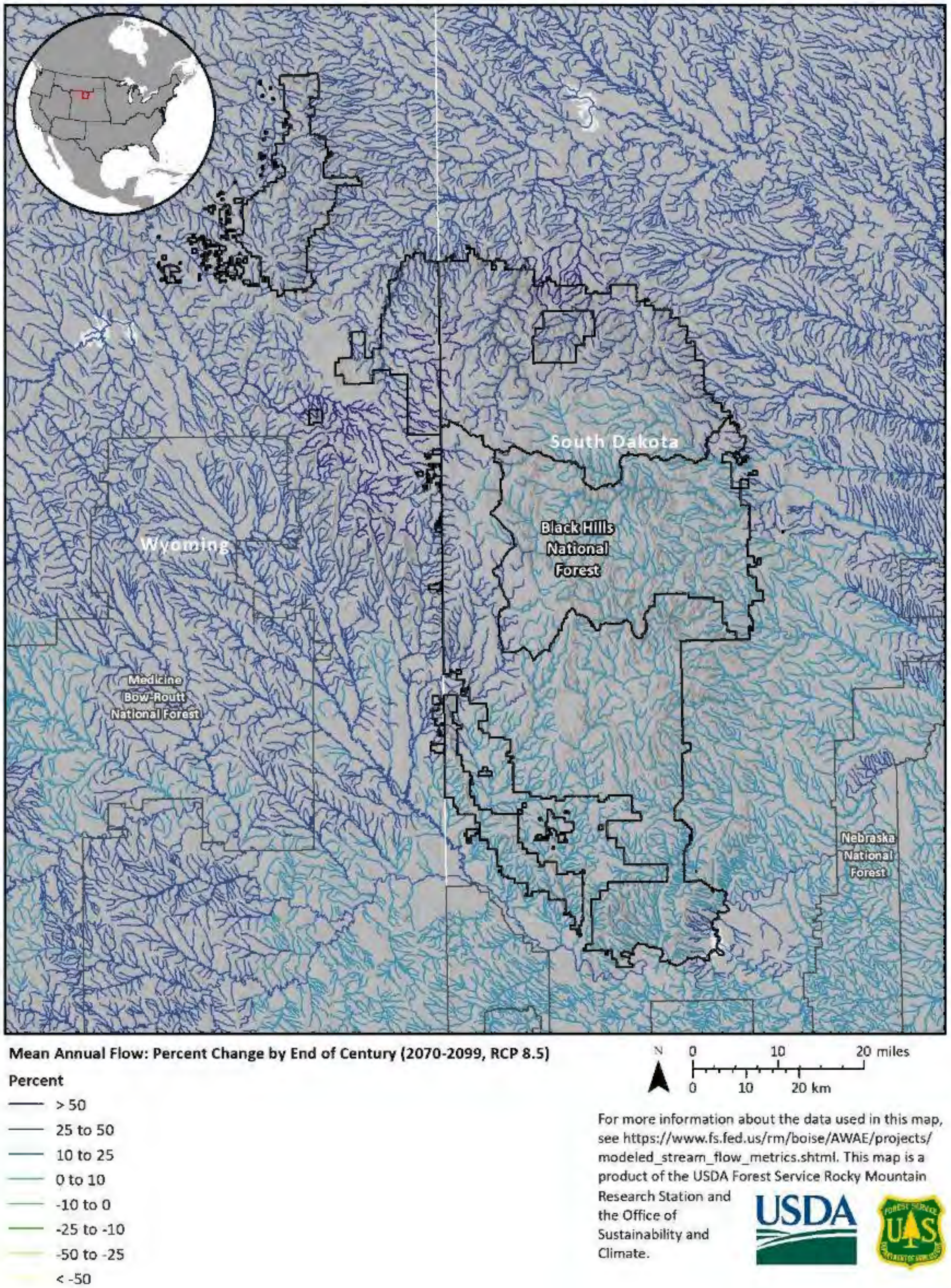
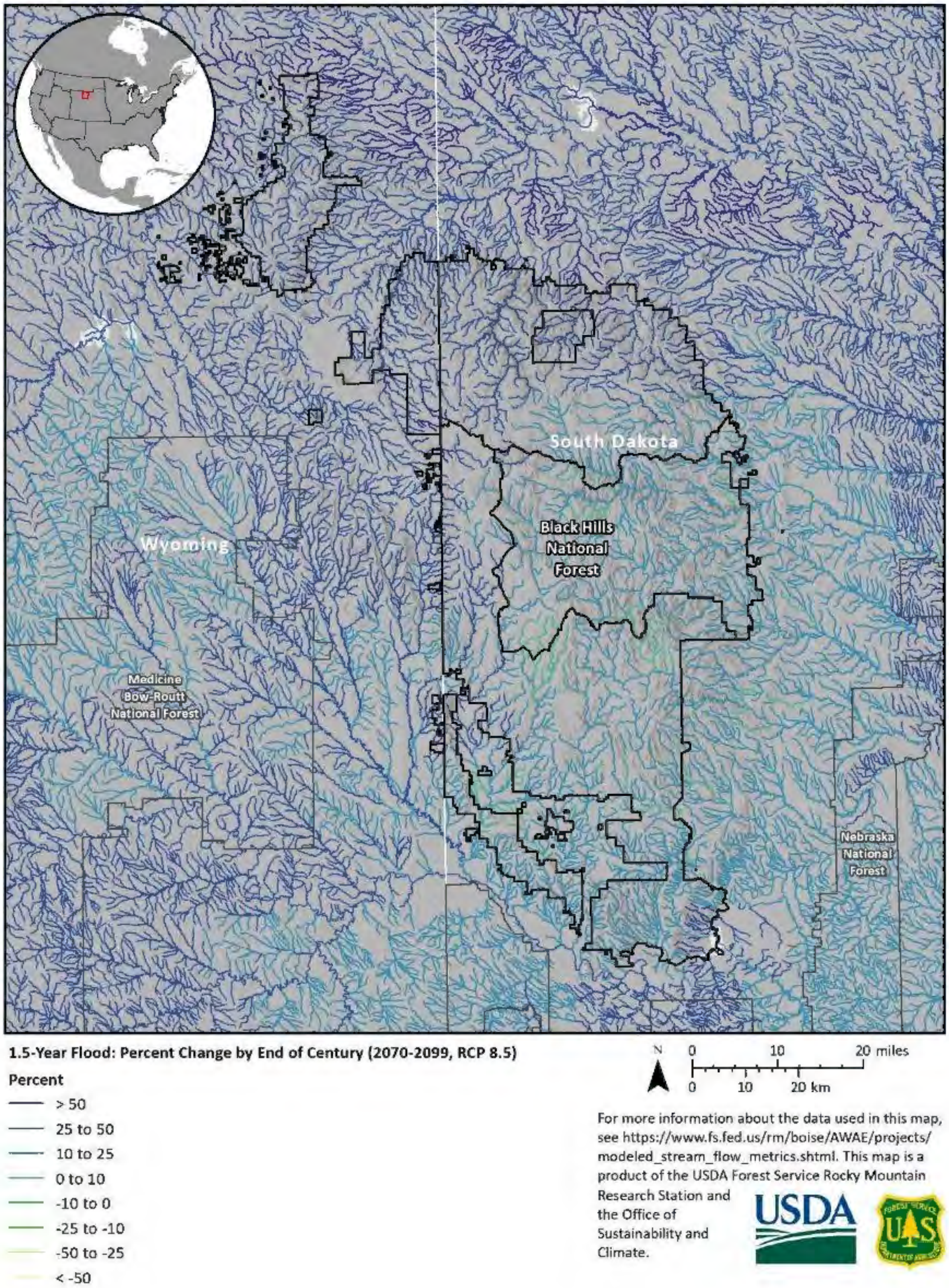


Figure 3-3. Projected changes in snow residence time (SRT) in the Black Hills National Forest region from historical conditions (1975–2005) to the 2080's (2071–2090) based on temperature increases projected from a 20 global climate model ensemble mean under RCP 8.5. Data and methods description are available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



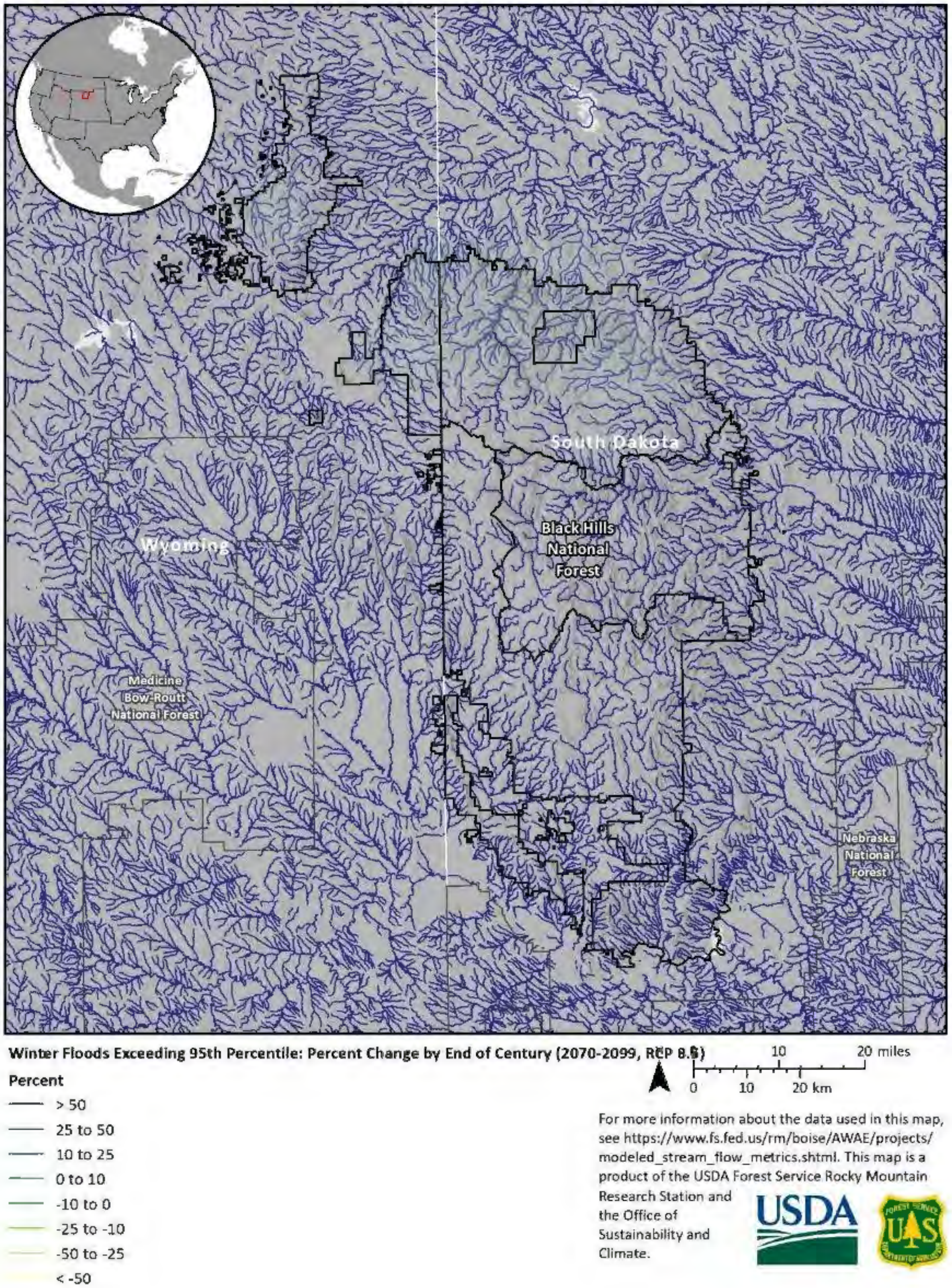
For more information about the data used in this map, see https://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml. This map is a product of the USDA Forest Service Rocky Mountain Research Station and the Office of Sustainability and Climate.

Figure 3-4. Projected percent change in mean annual flow between a historical period (1970–1999) and the 2080s under RCP 8.5, 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 1.5-year floods (bankfull flow) between a historical period (1970–1999) and the 2080s under RCP 8.5, 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 3-6. 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 RCP 8.5, based on Variable Infiltration Capacity (VIC) hydrologic modeling.

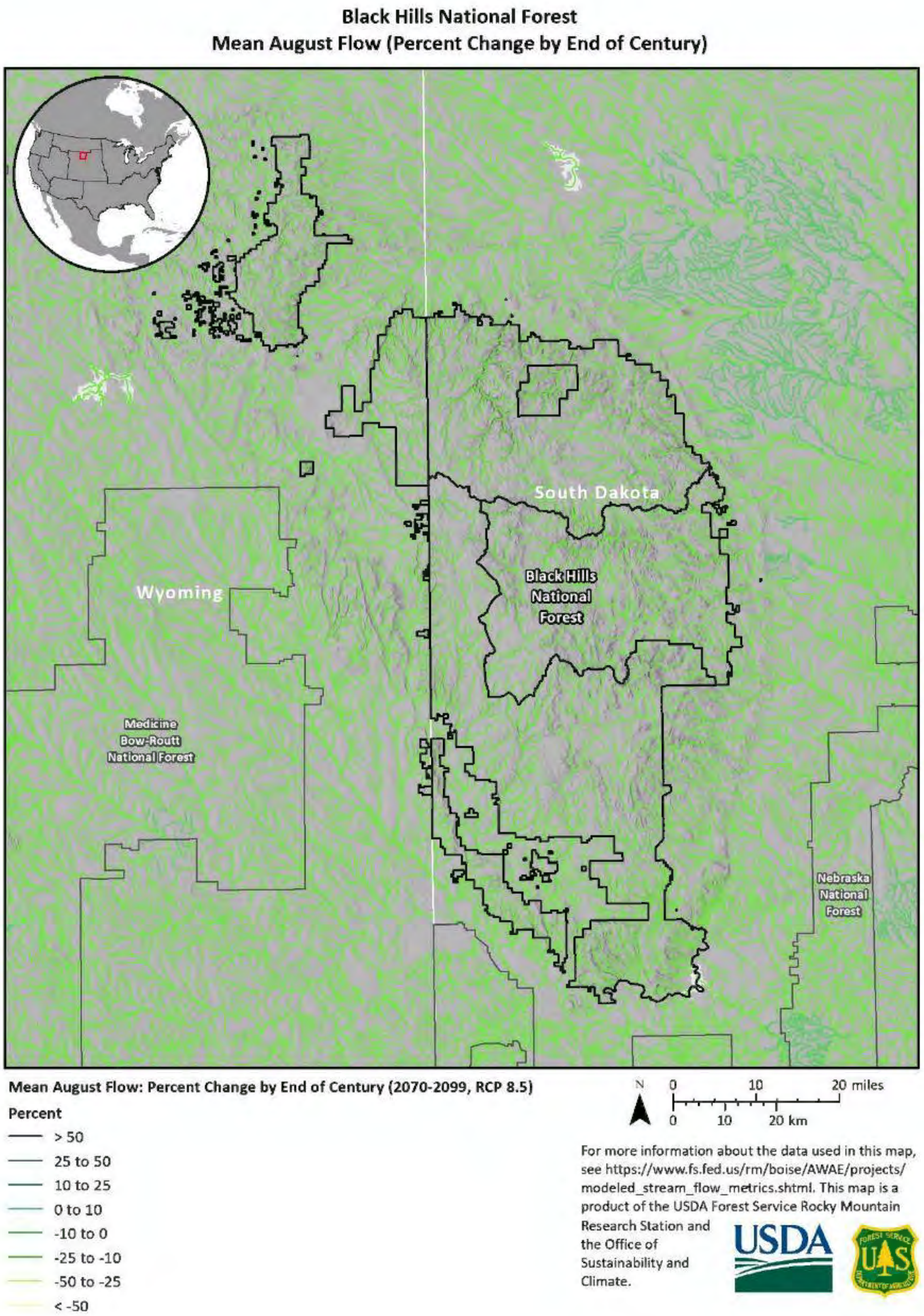
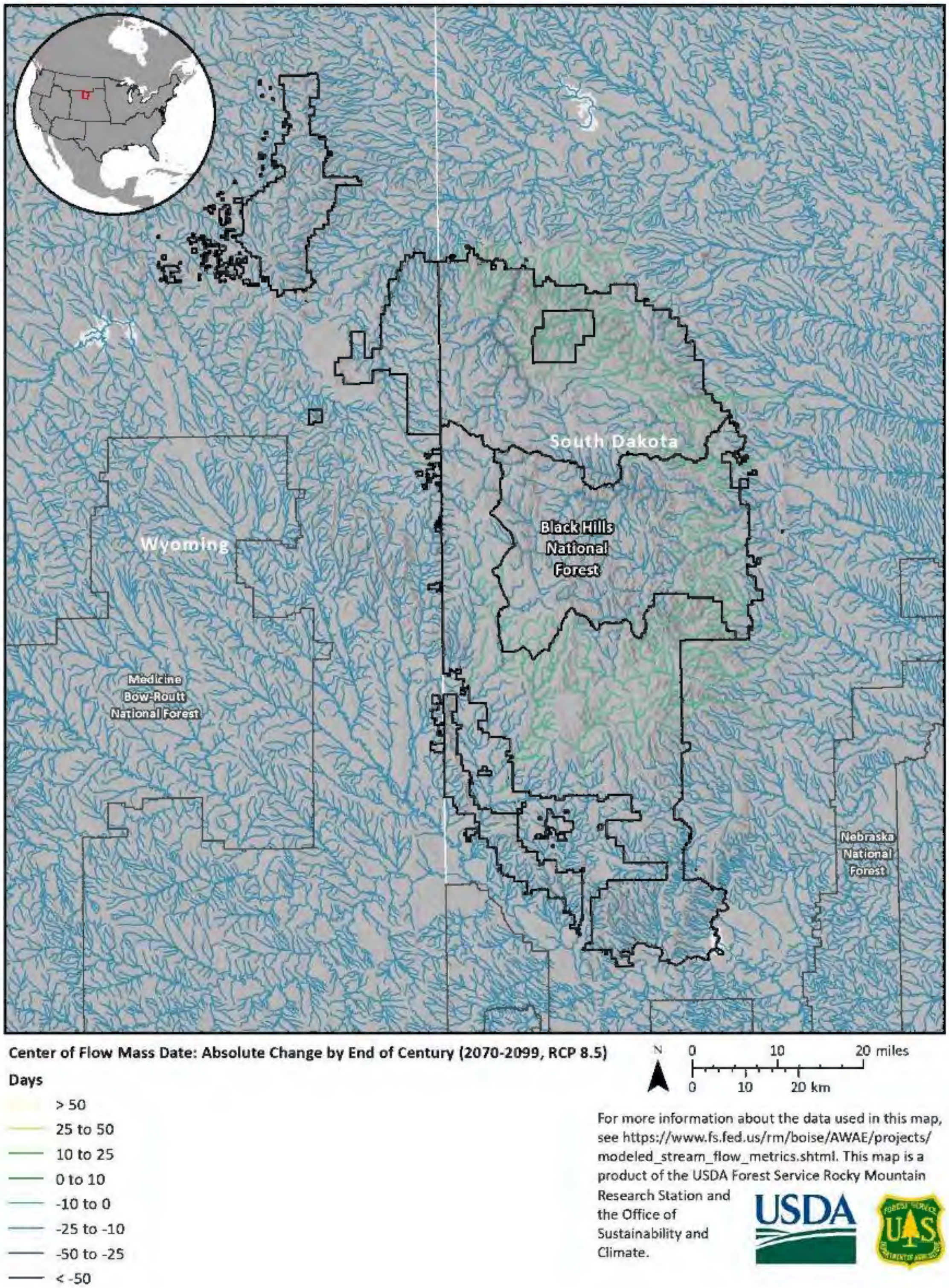


Figure 3-7. Projected percent change in mean August streamflow between a historical period (1970–1999) and the 2080s under RCP 8.5, based on Variable Infiltration Capacity (VIC) hydrologic modeling.



Center of Flow Mass Date: Absolute 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 3-8. Projected percent change in center of flow mass date (when the highest flows occur) between a historical period (1970–1999) and the 2080s under RCP 8.5, based on Variable Infiltration Capacity (VIC) hydrologic modeling.

4. Fish and aquatic ecosystems

Jessica Halofsky[6] and Dan Isaak[7]

Introduction

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 (Conant et al. 2018), earlier snowmelt-driven runoff (Figure 3-9), increased flooding (Figures 3-7), and more variable summer streamflows (Figure 3-8)[8], as well as indirect changes caused by shifts in disturbance regimes, including increases in wildfire (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 NF: 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 South Dakota Game, Fish, and Parks (SDGFP) database.

Climate change effects on lake chub

Lake chub are widely distributed across Canada and the northern portions of the U.S. The small populations in the Black Hills remain from the last glaciation. They are disjunct and isolated from other populations and at the southern extent of the species range. Historical

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

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 chub are spring spawners and usually breed in streams (Scott and Crossman 1973). Overall, the ecology of lake chub is not well 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, since there are no nearby populations to recolonize (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.

Climate change effects on mountain sucker

The Black Hills are at the eastern extent of the distribution of the mountain sucker, which is distributed across western North America (Belica and Nibbelink 2006). Most local 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).

Since perennial streams are critical to the mountain sucker, any enhanced flow variability from climate change that results in stream intermittency would likely have a negative effect on mountain sucker populations (Dauwalter and Rahel 2008). 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 59 and 75 °F, 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 mortality 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).

Climate change effects on 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 59–68 °F 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, warming rates may be slower in the groundwater-influenced habitats where finescale dace are currently found (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 trout species, 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.

Climate change effects on 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).

Climate change vulnerability of low-gradient mountain stream reaches

The regional ecosystem vulnerability assessment for the Rocky Mountain Region of the National Forest System provides additional information on the vulnerability of low-gradient mountain stream reaches, an aquatic ecosystem especially relevant to the Black Hills NF (Rice et al. 2018). Low-gradient mountain streams are particularly prominent in the Black Hills NF, which has the largest share (24%) of these stream reaches of national forests in the Rocky Mountain Region. Around 30% 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.

Low-gradient mountain streams have slopes less than 2% 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 absence of beavers in historical habitat have significantly impacted these ecosystems (Rice et al. 2018).

The vulnerability assessment determined that low-gradient mountain reaches have very high vulnerability. This reflects the current limited extent of these streams and the likelihood of future habitat fragmentation due to warming stream temperatures, though groundwater contributions may offset some effects of stream temperature increases, particularly in areas like the Black Hills where there are high levels of groundwater contribution. Loss of snowpack may also impact low-gradient mountain stream ecosystems, which depend on snow-driven hydrological regimes. Disturbance effects also contribute to this high vulnerability (Rice et al. 2018).

The vulnerability assessment also identified aspects of low-gradient streams that contribute to their ability to adapt to climate change. Wide valley bottoms slow the flow of water and transport of sediments. Shading from riparian vegetation reduces stream temperatures. Large wood features help regulate flows, and effects from beavers on hydrology may contribute to resilience in these systems (Rice et al. 2018).

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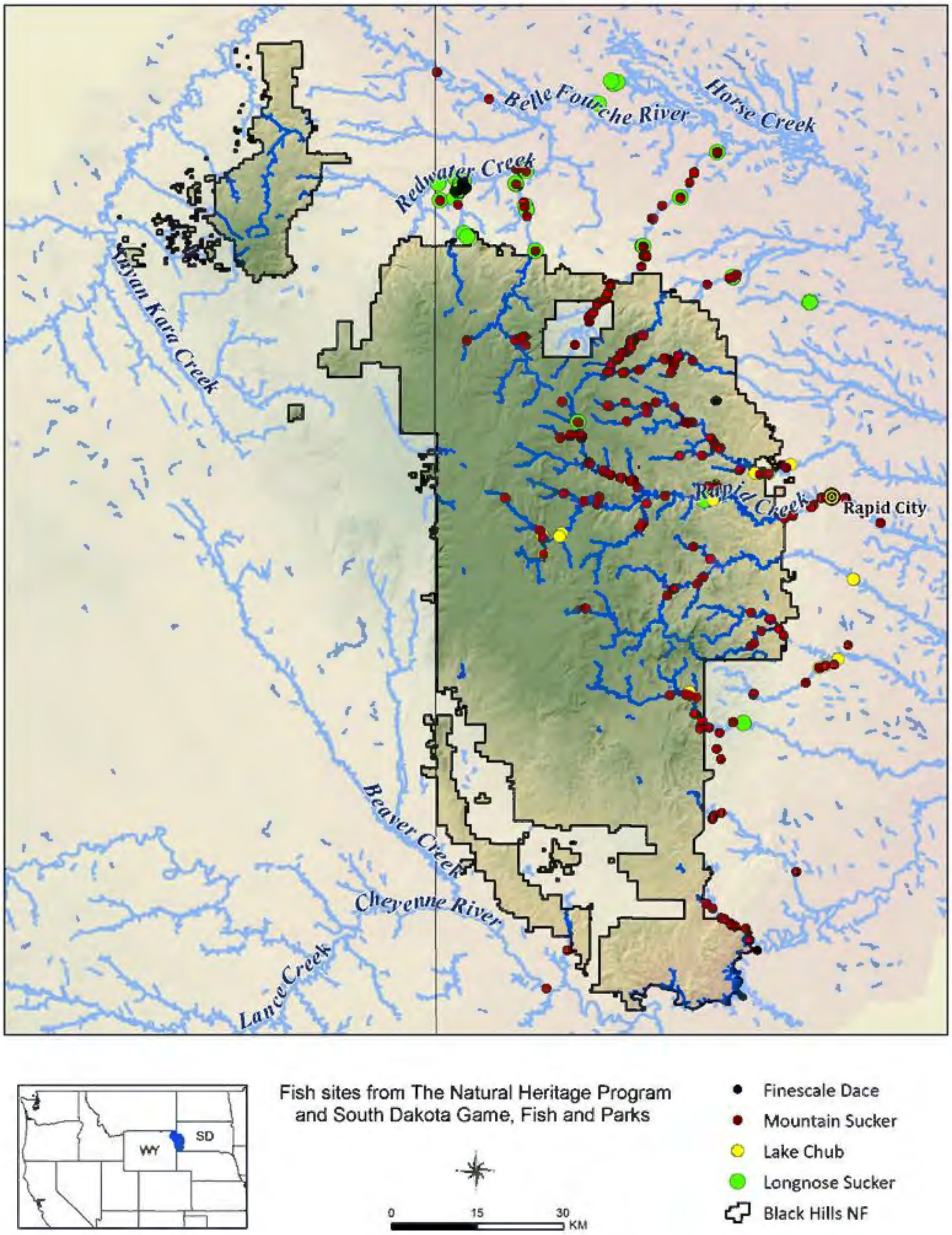

Figure 4-1. Distribution of finescale dace, mountain sucker, lake chub, and longnose sucker on the Black Hills National Forest (NF). Data are from the South Dakota Department of Game, Fish, and Parks database (https://ert.gfp.sd.gov/content/map).

5. Vegetation

Thomas Timberlake[9] and Emily Fusco[10]

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*) and white spruce (*Picea glauca*). 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. Natural 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 will thus 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

For water-limited forests found at lower elevations, including ponderosa pine forests in the Black Hills, increased temperatures will result in drought stress and decreased tree growth (Vose et al. 2016; Bottero et al. 2017). While increases in temperature and earlier snowmelt may result in longer growing seasons, particularly in higher elevation forests, these positive effects on tree growth are not expected to outweigh negative effects from increased drought stress (see Chapters 2 and 3). Drought stress also makes trees more susceptible to mortality from disturbances such as insect outbreaks, and changes in climate will influence conditions conducive to large-scale ecological disturbances that result in acute changes to ecosystem structure, composition, and function (Vose et al. 2016). These effects at the tree level can impact

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the overall structure, composition, and function of forests, which, in turn, will have negative effects on ecological integrity.

Climate projections discussed in Chapter 2 indicate that there may be a slight increase in precipitation in the future for the Black Hills; however, these projections also suggest that increases in precipitation may come during the winter before the growing season begins. In general, projections of precipitation are uncertain with magnitudes and directions of change varying across climate models. In addition, precipitation projections indicate that there will be higher interannual variability in precipitation; projected increases in precipitation are not likely occur in every year. Above all, climate projections indicate that temperatures will increase, which will increase evapotranspiration and drought stress. The negative effects on forest growth of increased temperature will likely outweigh any benefits of projected increases in precipitation.

Climate change effects on rangeland vegetation

There has not been research examining climate change vulnerability of rangeland vegetation in the Black Hills region specifically. Several studies have examined rangeland climate change vulnerability in the broader Northern Great Plains region; however, these studies generally do not include the Black Hills area, since it is primarily forested and higher elevation (e.g., Reeves et al. 2014). These studies are also generally oriented towards livestock production and may not cover other aspects of climate change effects on rangeland ecosystems (e.g., Derner et al. 2018). Even so, key conclusions from studies of this broader region may be useful for management of rangeland vegetation and associated uses on the Black Hills National Forest.

Model projections suggest that net primary productivity in rangeland vegetation will increase in the Northern Great Plains in the future over the long term; however, these increases are not projected to occur until after the year 2030. For the Northern Great Plains, temperature is the bioclimatic driver most responsible for these projected trends in net primary productivity, though increases in CO_2 and changes in precipitation are also drivers and more influential in other regions (Reeves et al. 2014). These projected increases in net primary productivity may eventually result in increases in forage quantity and a longer season over which forage is available (Reeves et al. 2014; Derner et al. 2018). However, potential benefits for wildlife and livestock grazing may be offset by decreases in forage quality, expansion of invasive grasses, more frequent drought, and year-to-year variability (Reeves et al. 2017; Briske et al. 2021).

Climate projections suggest increases in year-to-year variability in temperature and precipitation. Drought conditions are expected to become more frequent, particularly in summer months and in years with hotter temperature and lower precipitation totals. Drought may result in decreases in productivity and increases in plant mortality for rangeland vegetation (Vose et al. 2016). Climate change may also increase the vulnerability of rangeland vegetation to the spread and establishment of invasive annual grasses, particularly in conjunction with more widespread wildfire (Vose et al. 2016). These conclusions derive from studies conducted at broader geographic scales, and climate effects on rangeland and understory vegetation in the Black Hills may be an important topic for future study.

Climate change effects on disturbance processes

Most impacts of climate change on forests will occur indirectly through effects of climate change on disturbance processes (Keane et al. 2015; McKenzie et al. 2009; Peterson et al. 2014). 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).

Drought

Warming temperatures are likely to result in droughts that have 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 increased evaporative demand, which can make the effects of a lack of moisture more acute in terms of reduced growth and increased mortality rates (Frankson et al. 2022). These effects of drought may counteract potential benefits to tree species from longer growing seasons and slight increases in winter precipitation projected to occur in the Black Hills. Across the western United States, years with high acres burned correlate with years with drought conditions, and thus increasing drought under climate change will likely result in more widespread fire (Peterson et al. 2014).

Insect outbreaks

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, 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, to influence insect dynamics (Bentz et al. 2010). Periodic insect outbreaks have affected the Black Hills over a long period of time, with a notable outbreak occurring around the turn of the 20th Century. A more recent outbreak occurred in the early 2000s (King et al. 2013; Negrón et al. 2017). Climate-driven increases in drought conditions may lead to increases in tree mortality from beetle outbreaks.

Fire

Higher temperatures and altered precipitation patterns affect wildfire patterns. Climate is a key control on wildfire regimes, and recent studies have documented correlations between area burned and 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 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). With warming, firefighters will likely 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 on wildfire and climate change 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, and that climate change will contribute to increases in wildfire activity in the future compared to the present day. 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). These projections of increases in wildfire align with the climate projections in Chapter 2, which indicate a projected increase in temperature throughout the year and that any projected increases in future precipitation would likely be concentrated in the winter and spring, rather than during the summer fire season. There is not conclusive evidence that climate change will affect wind, another factor that affects wildfire behavior.

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 extremely low fuel moisture (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.

Climate change effects on tree species in the Black Hills

This section synthesizes information on climate change impacts on several important tree 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 determined 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 its widespread range, ponderosa pine is adapted to a broad range in moisture availability and is generally drought tolerant. However, decreases in moisture availability may limit growth and regeneration. Research in the Black Hills indicates that drought conditions limit tree growth, especially in higher density forests (Bottero et al. 2017; Gleason et al. 2017). 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, and projected decreases in snowpack in some areas may result in decreased growth (Gleason et al. 2021). These impacts from drought stress, loss of snowpack, and increased disturbance will likely outweigh any benefits in growth associated with a longer growing season or increases in precipitation.

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 historical 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 warmer temperatures, 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 ponderosa pine. 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 compared to other areas of ponderosa pine forests, the Black Hills generally have consistent periods of reliable moisture promoting seed development and germination. These periods of reliable moisture may continue to occur in the future, but they may not occur as frequently if year-to-year variability in precipitation increases. 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 that remove seed-bearing trees. The Black Hills population is one of the most eastern ponderosa pine populations. This position 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 historical 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 the thick bark of old trees and other adaptations that confer resistance to surface fire (King et al. 2013). This study's conclusions countered the findings of another study that used 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 envelope modelling (Iverson and McKenzie 2013).

As discussed above, climate change will likely contribute to increases in wildfire in many areas. Older ponderosa pine trees have structural traits, including thick bark and self-pruning lower limbs, that confer relatively high resistance to fire (Stevens et al. 2020). As such, ponderosa pine forests may be resilient to climate-driven changes to fire regimes in the Black Hills; however, this will also depend on how current forest structure and fuel conditions contribute to fire risk and effects of climate change on fire behavior. Denser homogenous forests and ones dominated by younger trees may be most vulnerable to increases in fire related to climate change (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, including at ten years after the fire (Lentile et al. 2005; Keyser et al. 2008; Stevens-Rumann et al. 2012). At a landscape scale, the Jasper Fire burned at mixed severity, leaving a mosaic of structural conditions (Keyser et al. 2008). One study that examined several fires, including the Jasper Fire, 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 impact ponderosa pine forests. 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 tree susceptibility to pine beetles (Bentz et al. 2010; Rice et al. 2018). 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 widespread ponderosa pine mortality (Negrón et al. 2017; Steen-Adams et al. 2021). Intensified drought conditions in the future may increase risks of large-scale mortality during insect outbreaks.

White spruce (*Picea glauca*)

White spruce is a shade-tolerant, slow-growing species. In the Black Hills, it is found primarily on 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.

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 (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). While these studies were focused on regions located farther to the north, their conclusions suggest that white spruce in the Black Hills are vulnerable to increases in drought expected with increased temperatures.

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, the Black Hills currently provides a refugia for white spruce, a boreal species, and 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 (Stralberg et al. 2020).

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 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 for the species from fire as well as drought.

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, and the extent of aspen on the forest is decreasing as a result of replacement by pine and spruce in some areas (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 41 and 77°F, photosynthesis rates decrease above 77°F (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 (*Quercus macrocarpa*) is more abundant than aspen (Walters et al. 2011). Aspen stands in the Black Hills are primarily located on north-facing aspects and other wetter sites (Severson and Thilenius 1976). These cooler and wetter sites may continue to support the species under warmer drier future climates; however, 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 because it relies on historical climate relationships and does not account for key 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 because 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 suggested 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) 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 in moist ravines and riparian areas (Sieg 1991). There is some evidence of hybridization of bur oak and gambel oak (*Quercus gambelii*) in the Black Hills, which may contribute to its shrubby characteristics in the area (Maze 1968). There is limited research on hybridization of these two oak species, and implications for the adaptive capacity of oak in the Black Hills are unknown.

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 in that region, 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 acorn size may be directly related to environmental variables, with oaks on 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. 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. However, it is unclear if climate change would affect this aspect of bur oak in the Black Hills (Sieg 1991).

As noted above, some bur oak in the Black Hills may be hybridized with Gambel oak. Gambel oak's range is located well south of the Black Hills, and some research indicates that the hybridization in the Black Hills may have occurred during a postglacial warm period (Maze 1968). Other climate change vulnerability assessments have noted a relatively low vulnerability to climate change for Gambel oak given its drought tolerance and ability to resprout following fire (Halofsky et al. 2018). This suggests that hybridized oaks in the Black Hills may be especially well adapted to future conditions; however, further research on this topic is needed.

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 Battaglia 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 CO_2 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*) 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.

<u>Rocky Mountain juniper (*Juniperus scopulorum*)</u>

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. However, high temperatures can negatively impact juniper growth and regeneration (Halofsky et al. 2018). Climate change effects on fire are more likely to affect juniper.

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 monotypic stands following 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 (*Corylus cornuta*), 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 to 60°F, while average maximum temperatures will increase from 85 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, Swanston 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 locations receiving varied precipitation amounts and patterns (Safford et al. 1990), it is likely to be moisture limited in the Black Hills (Sieg 1990), and further declines in moisture availability would decrease suitability. However, areas that retain moisture in a warmer future may offer refugia for paper birch populations (Stralberg et al. 2020).

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 and have 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 CO_2 increased flowering, seed weight, germination rates, and seedling vigor (Darbah et al. 2008). However, elevated CO_2, 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 in 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 fungi *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).

Summary for 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 be 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 negatively impact tree growth and increase mortality rates for the species, and large high-severity disturbances may adversely impact regeneration patterns.

The Black Hills NF contains several species that resprout following fire, which may benefit 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 populations in the Black Hills located at the southern extent of their species ranges. As such, these two species are likely to be particularly vulnerable on the National Forest to changes in climate. Even so, the Black Hills may continue to support refugial population of these species, particularly in colder, wetter locations.

Current forest conditions will affect the sensitivity of ecosystems to climate change. Ponderosa pine stands that are currently denser and more homogenous than pre-settlement conditions may be particularly vulnerable to impacts from drought and fire. In addition, older trees that have developed thick bark are more resistant to fire than younger ponderosa pine. Species like white spruce may currently occupy sites to which they are not well suited because of long-term fire exclusion, and these populations in particular may be vulnerable to effects of increases in temperatures.

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 drought. Similarly, strategies that restore and maintain key ecological processes and functions will be important for preparing systems for climate change.

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6. Recreation

David L. Peterson[11]

Summary

- Higher temperatures will extend the duration of the season favorable for warm-weather recreation (e.g., nature viewing, hiking, camping), 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 and reservoirs, like Pactola Lake, 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 flow, which will affect the distribution of desirable species for angling in streams. 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, there will be fewer opportunities for snow-based recreation (snowmobiling, cross-country skiing, downhill skiing), 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. 2022). 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

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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). 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 underestimates 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 (Figure 6-1). 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, Buffalo Gap National Grassland—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 (*Odocoileus hemionus*) and white-tailed deer (*Odocoileus virginianus*). 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 (Figure 6-2). 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, user values, and resources. 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) (Figure 6-3), 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 Chapters 2 and 5) 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, suggesting that females are underrepresented in current recreation patterns. 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 OHV 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%), and groceries (12%). The highest spending categories for local visitors differ considerably: gasoline and oil (27%), groceries (24%), restaurants (13%), and 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) (Figure 6-4). 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. 2022; O'Toole et al. 2019, Peterson et al. 2022; Winter et al. 2021). 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 NF. 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. 2021).

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, 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. 2022, Peterson et al. 2022). 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. More widespread fire in the future may lead to reduced visitation. For some recreationists, perceptions of increased risks from fire or fire closures may also affect their decisions to visit the Black Hills.

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, concessionaire agreements, and necessary activities like garbage collection and facility cleaning. Providing recreational opportunities over a longer season may also be more costly.
- The frequency and extent of wildfire will likely increase in the Black Hills region (Figure 6-5). 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 Chapter 3).

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). The Black Hills NF may face increased pressure for water-based recreation on reservoirs like Pactola Lake and Deerfield Lake if drought conditions result in decreased water levels that impede access at lower elevation reservoirs in the region, like Angostura Reservoir, Keyhole Reservoir, and Belle Fourche Reservoir. 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.

- 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 2000 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 is 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.
- Effects of climate change on species like aspen and paper birch, which provide habitat for key wildlife species, may decrease opportunities for wildlife viewing. Declines in these species may also affect opportunities for visitors to view fall colors associated with deciduous tree species.

- 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 *[Pomoxis annularis]*, perch [*Perca flavescens*], and walleyes [*Sander viterus*]) will determine whether or not sportfishing is affected. 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 7,242 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). Warming and decreased snowpack may thus decrease demand for skiing. 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. During low snow years, continued use of snowmobiles may result in damage to vegetation and soil due to a lack of snow cover to protect these resources (Fassnacht et al. 2018). If recreationists shift their participation from snowmobiling to OHV use during winter or shoulder seasons, this trend may exacerbate existing challenges associated with OHV use on the Black Hills NF.

Effects on Snow-based Activities in Black Hills National Forest

- The duration of the season for snow-based activities will decrease greatly, especially by the mid to late 21st century (Figure 6-6).
- 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. Ski areas may also adapt by providing more summer recreational opportunities, including, for example, mountain biking trails.

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.

In addition to 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, an 8.9% increase, 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. Preparing for expected increases in visitation, particularly for warm-weather activities, may require cross-boundary planning in collaboration with other recreation managers in the Black Hills region and the broader landscape.

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 able to adapt to changing conditions by changing locations and activities (Miller et al. 2022). 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.

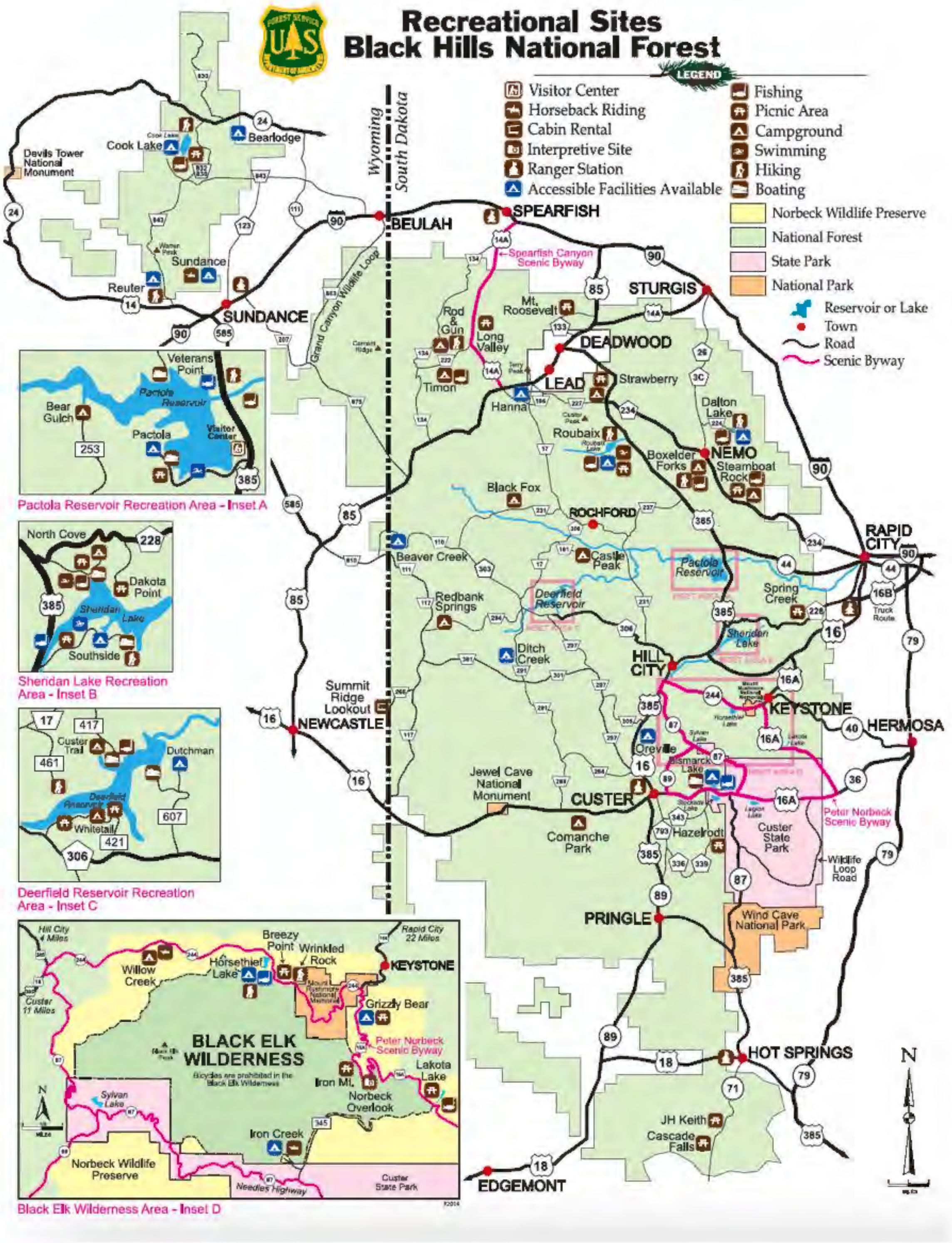


Figure 6-2. Signs at Gold Run trailhead, Black Hills NF. Numerous trailhead signs in the forest are in disrepair and have minimal information on trails and natural resources. Walking surfaces for viewing and access are often unmaintained.

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. (2022).

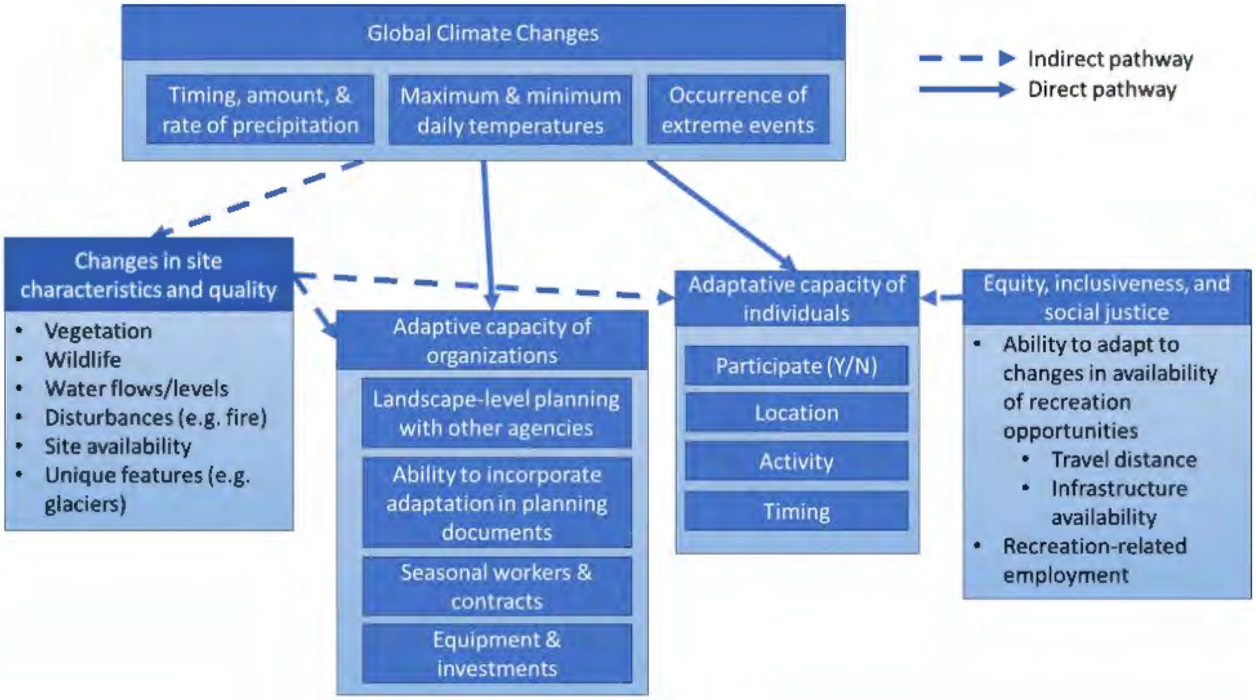
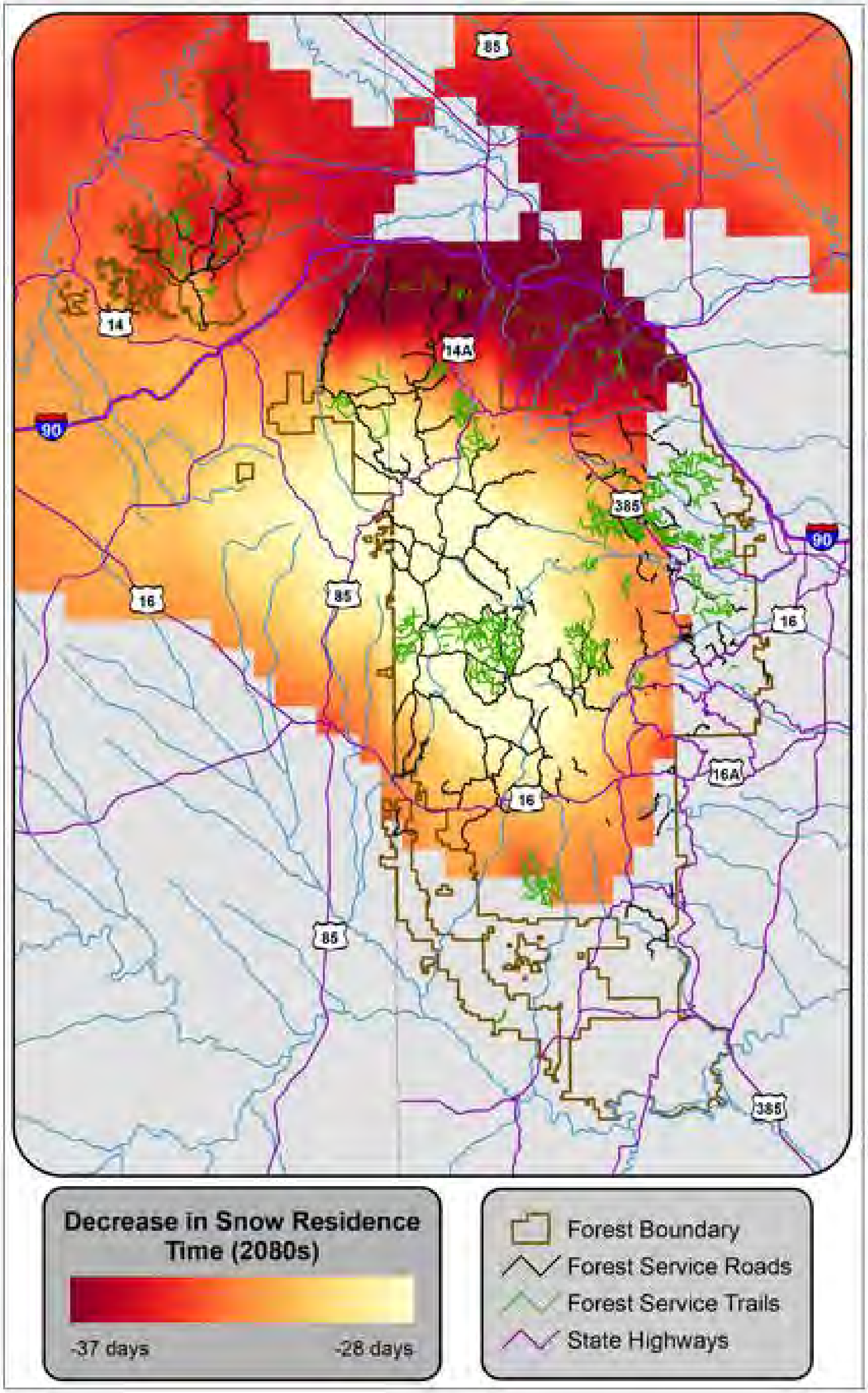
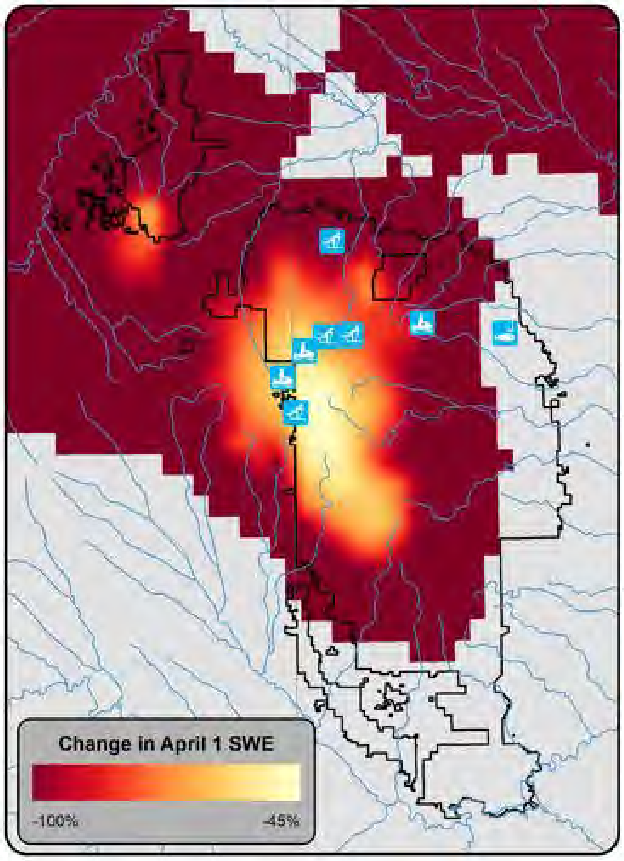
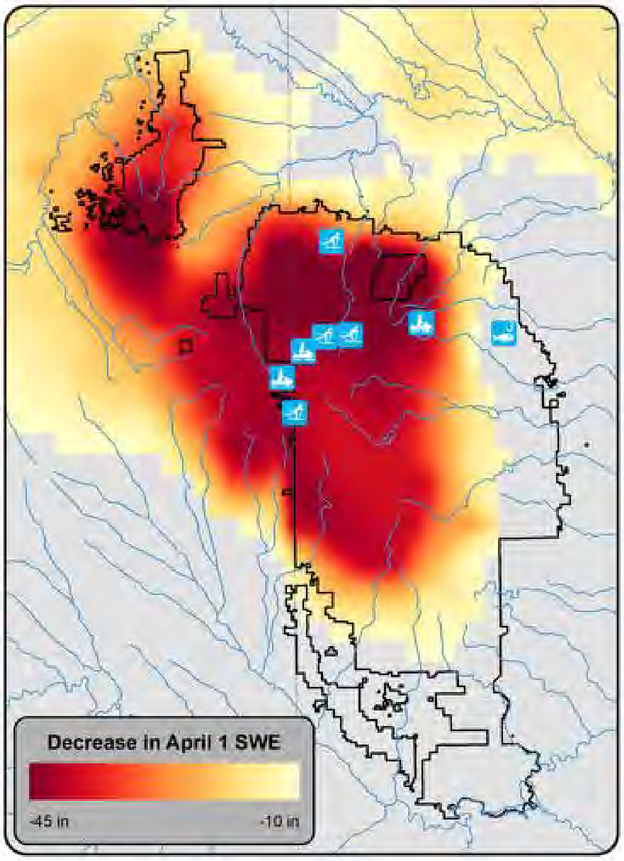


Figure 6-5. The Jasper Fire burned with mixed severity across 83,000 acres in the South Black Hills in summer, 2000. Image from Google Earth, posted at https://www.sdpb.org/blogs/news-and-information/forest-service-works-to-erase-the-jasper-fire-scar-in-black-hills.

Figure 6-6. 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). Maps by Rob Norheim.




Change in April 1 SWE
-100%
-45%


Decrease in April 1 SWE
-45 in
-10 in