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U.S. Geological Survey North Central Climate Adaptation Science Center

Prepared in cooperation with the University of Colorado Boulder

Synthesis of Climate and Ecological Science to Support Grassland Management Priorities in the North Central Region

Open-File Report 2023–1036

U.S. Department of the Interior
U.S. Geological Survey

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Preface

This report presents findings from the project “A Synthesis of Climate Impacts, Stakeholder Needs, and Adaptation in Northern Great Plains Grassland Ecosystems” (hereafter, the Grasslands Synthesis Project) led by the North Central Climate Adaptation Science Center (NC CASC). Grassland ecosystems in the NC CASC region support local economies, Tribal communities, livestock grazing, diverse plant and animal communities, and large-scale migrations of ungulates and multiple bird guilds. Understanding how climate change and variability will impact grassland ecosystems is crucial for successful management of grasslands in the 21st century. The NC CASC began the Grasslands Synthesis Project in 2020 to establish a baseline of information to best serve its resource managers and help meet regional grassland management goals. This project had two primary goals: (1) to synthesize the management goals and challenges for grassland managers across the region and (2) to assess the state-of-the-science and identify knowledge gaps for addressing these goals and challenges within the context of climate change. The publication of the “Grassland Management Priorities for the North Central Region” report (Miller Hesed and Yocum, 2023) report accomplished the first goal, which identified information needed to meet grassland management goals in the North Central region within the context of climate change. This report addresses those identified information needs by synthesizing the existing climate and ecological science relevant to grassland management priorities and identifying where more research is needed.

The NC CASC is a partnership between the U.S. Geological Survey (USGS), the University of Colorado Boulder, and five consortium partners—Conservation Science Partners, Great Plains Tribal Water Alliance, South Dakota State University, University of Montana, and Wildlife Conservation Society. The NC CASC is part of a network of regional Climate Adaption Science Centers (fig. Pr1) that serve resource managers by developing the science and tools needed to address the impacts of climate change on the Nation’s land, water, fish, wildlife, and cultural heritage resources. The NC CASC serves Federal, State, and Tribal resource managers in Montana, Wyoming, Colorado, North Dakota, South Dakota, Nebraska, and Kansas.

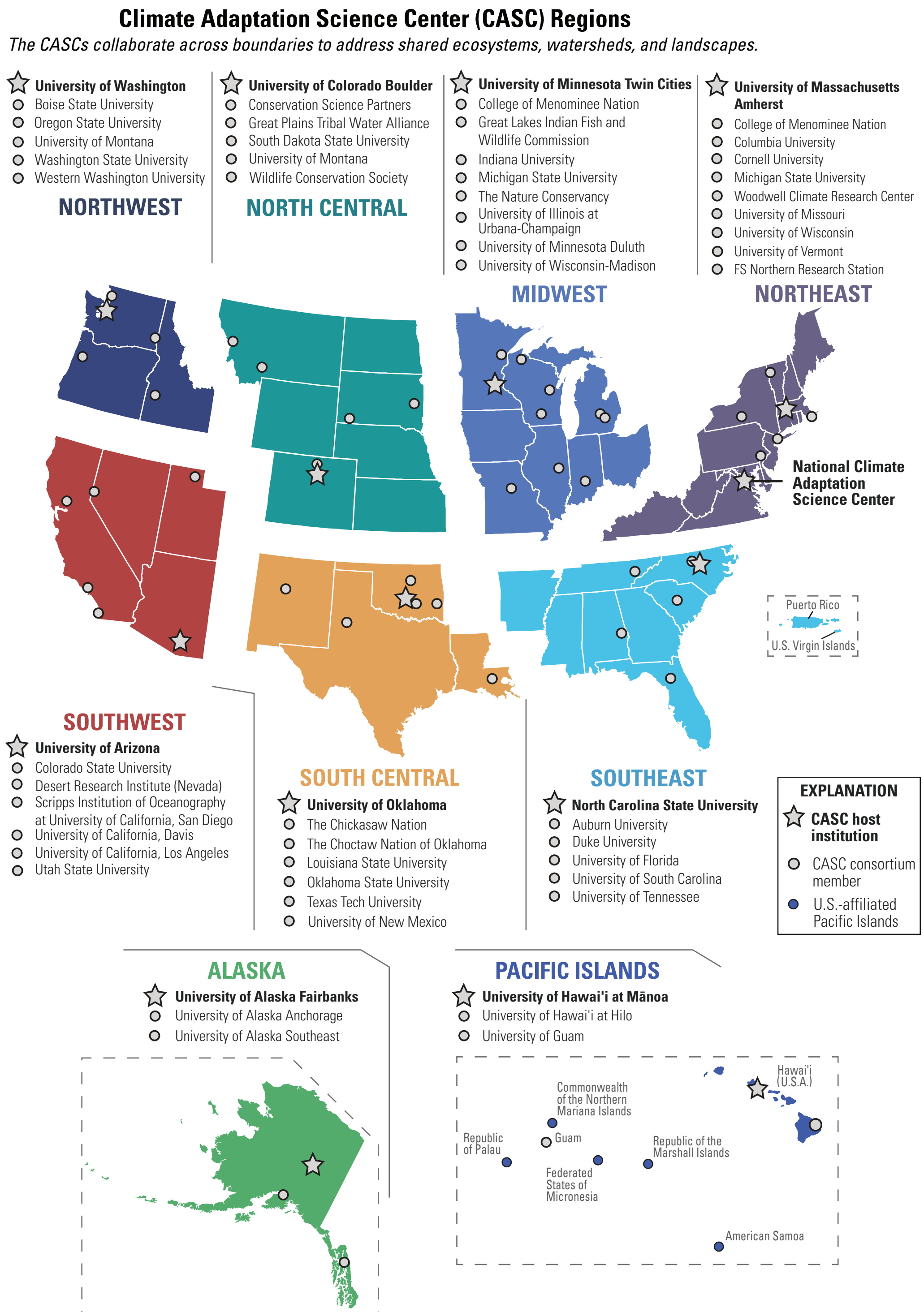

Figure Pr1. Schematic diagram of the Climate Adaptation Science Center Network and its associated territories and affiliated Pacific islands showing the Climate Adaptation Science Center regions overlain by the location of the National Climate Adaptation Science Center, CASC host institutions, and CASC consortium members.

Acknowledgments

We are grateful to the members of the Management Priorities Working Group and the Advisory Committee for cooperatively engaging in the generation of results presented in this report. The Management Priorities Working Group consisted of Marissa Ahlering (The Nature Conservancy [TNC]), Aparna Bamzai-Dodson (U.S. Geological Survey [USGS]), Jon P. Beckmann (Kansas Department of Wildlife and Parks), Emily Boyd-Valandra (Sicangu Lakota Oyate and Rosebud Sioux Tribe), Biologist and Indigenous Conservation Consultant), Molly Cross (Wildlife Conservation Society), Kimberly R. Hall (TNC), Brian Miller (USGS), Danika Mosher (National Park Service Research Assistant, Student contractor to USGS), James Rattling Leaf, Sr. (Great Plains Tribal Water Alliance), Ian Tator (Wyoming Game and Fish Department), and Ben Wheeler (Pheasants Forever and Quail Forever). The Advisory Committee included David Augustine (U.S. Department of Agriculture [USDA], Agricultural Research Service), Katie Bills Walsh (USDA, Agricultural Research Service), Alice Boyle (Kansas State University), Anthony Ciocco (Bureau of Indian Affairs), Lisa Dilling (Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder), Laura Edwards (South Dakota State University), Brad Guhr (Dyck Arboretum of the Plains), Brice Hanberry (USDA, Forest Service), Chris Helzer (TNC), Rachel Keen (Kansas State University), Doug Kluck (National Oceanic and Atmospheric Administration), Brian Obermeyer (TNC), Kim O'Keefe (University of Wisconsin-Madison), Graeme Patterson (Joint Venture 8 [JV8] Central Grasslands Conservation Initiative), Dave Pellatz (Thunder Basin Grasslands Prairie Ecosystem Association), Ronald Pritchert (U.S. Fish and Wildlife Service), Geri Proctor (USDA, Forest Service), Alden Shallcross (Bureau of Land Management), Madeleine Rubenstein (USGS), Stefan Tangen (Great Plains Tribal Water Alliance), Alisa Wade (USGS), Catherine Wightman (Northern Great Plains Joint Venture), and Ben Zuckerberg (University of Wisconsin-Madison). We also wish to thank Sean Finn (U.S. Fish and Wildlife Service) and David Mushet (USGS) for their review of the entire report.

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Mass	
kilogram (kg)	2.205	pound, avoirdupois (lb)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8.$$

Abbreviations

ARS	U.S. Department of Agriculture, Agricultural Research Service
C_3	photosynthetic pathway used by cool season grasses in which the first carbon compound produced contains three carbon atoms
C_4	photosynthetic pathway used by warm season grasses in which the first carbon compound produced contains four carbon atoms
CIRES	Cooperative Institute for Research in Environmental Sciences
CO_2	carbon dioxide
NC CASC	North Central Climate Adaptation Science Center
NGO	nongovernmental organization
TNC	The Nature Conservancy
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey

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Abstract

Grasslands in the Great Plains are of ecological, economic, and cultural importance in the United States. In response to a need to understand how climate change and variability will impact grassland ecosystems and their management in the 21st century, the U.S. Geological Survey North Central Climate Adaptation Science Center led a synthesis of peer-reviewed climate and ecology literature relevant to grassland management in the North Central region (Montana, Wyoming, Colorado, North Dakota, South Dakota, Nebraska, and Kansas). This synthesis begins to address grassland managers' information needs and identify research gaps. This report summarizes the impacts of climate change and variability on temperature, water availability, wildfire, vegetation, wildlife, large-bodied ruminants, grazing, and land-use change and the implications for grassland management in the North Central region. This report also identifies areas in which further research is needed.

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Introduction

Grasslands are one of the most endangered ecosystems in the world (Knopf and Samson, 1997; Samson and others, 2004; Bardgett and others, 2021); although they occupy nearly 54 percent of global terrestrial landmass, less than 5 percent are legally protected worldwide (Hoekstra and others, 2005). Grassland ecosystems exist in each of the seven States (Montana, Wyoming, Colorado, North Dakota, South Dakota, Nebraska, and Kansas), in the region (hereafter referred to as the "North Central region") serviced by the U.S. Geological Survey North Central Climate Adaptation Science Center (NC CASC). Much of the grasslands in the North Central region have been diminished and degraded by human land use. Understanding how climate change and variability will interact with existing stressors to impact grassland ecosystems is crucial for successful management of grasslands in the 21st century. In 2020, the NC CASC began a project to establish a baseline of information to best serve grassland managers (that is, those who develop grassland management plans or implement those plans on the ground) at Federal, State, and Tribal agencies and nongovernmental organizations (NGOs) and to help meet regional grassland management goals. This project, "A Synthesis of Climate Impacts, Stakeholder Needs, and Adaptation in Northern Great Plains Grassland Ecosystems" (hereafter, the Grasslands Synthesis Project), had two primary goals: (1) to synthesize the management goals and challenges for grassland managers across the region and (2) to assess the state-of the-science to identify knowledge gaps for addressing these goals and challenges within the context of climate change. This report meets the second goal by addressing the grassland management information needs that were identified in "Grassland Management Priorities for the North Central Region" (Miller Hesed and Yocum, 2023). Because of the multidimensional nature of the information needs, which require consideration of interconnections among many factors, the authors of this synthesis employed a narrative-style literature review to "synthesize insights from a variety of perspectives and disciplines, or areas where insufficient data exists [sic] to conduct a systematic review or meta-analysis" (Sovacool and others, 2018, p. 23). Although this report does not address all identified information needs, we reviewed and summarized relevant climate change observations and projections and their expected effects on water availability, wildfire, vegetation, wildlife, grazing, and land-use change. A forthcoming, full report is planned to provide more detail on each of these topics and identify areas where additional research is needed.

Climate Change Observations and Projections

Temperatures across the North Central region have increased by 1–2 degrees Fahrenheit (°F) since the early 1900s (Vose and others, 2017; Mufson and others, 2019), and they are projected to increase by 4–6 °F by the mid-21st century and 5–10 °F by the late-21st century, depending on future greenhouse gas emissions (Ojima and others, 2021). Precipitation has increased across much of the region in all seasons (Garbrecht and others, 2004; Easterling and others, 2017; Zhang and others, 2021). Climate models project significant increases in winter and spring precipitation and plausible decreases in summer precipitation (Easterling and others, 2017; Whitlock and others, 2017). Warmer temperatures are expected to offset increases in future precipitation and affect water demand and availability (Vicente-Serrano and others, 2020). Changing seasonal patterns of water availability such as soil moisture or streamflow are expected, which could include wetter springs and drier late-summers and falls (Mankin and others, 2017). Rapidly evolving (flash) droughts and hotter droughts are projected to increase because of a warmer atmosphere and increases in the atmospheric evaporative demand (thirst; Bradford and others, 2020; Pendergrass and others, 2020). The North Central region is prone to large year-to-year variability in temperature and precipitation. Climate change is expected to further increase the magnitude of this variability (Conant and others, 2018; Douville and others, 2021).

Water Availability and Wildfire

Climate change impacts on temperature and precipitation will in turn impact water availability and wildfire behavior. Increased temperatures will result in more precipitation falling as rain rather than snow in the future (Trenberth, 2011), leading to more runoff and streamflow in winter and spring and decreased runoff and streamflow in late summer and fall, with some spatial variation (Bureau of Reclamation, 2016). The Missouri Basin in Colorado has experienced increases in annual runoff in the eastern parts and decreases in the western and southern parts of the basin since the 1960s (Norton and others, 2014; Dudley and others, 2019). Future projections suggest modest increases in annual streamflow across much of the basin, but with potential decreases seasonally in late summer and fall (Qiao and others, 2014; Conant and others, 2018). However, extreme events and large interannual variability will have a greater influence on water availability in the region as compared with mean changes in the climate (Conant and others, 2018; Douville and others, 2021).

There is considerable uncertainty on how changes in temperature, precipitation, snow, and runoff will affect groundwater recharge (Crosbie and others, 2013; Niraula and others, 2017). Current rates of groundwater extraction in the northern Great Plains (which includes the grassland ecoregions in Montana, Wyoming, North Dakota, South Dakota, and northern Nebraska) are expected to be sustainable (Conant and others, 2018). Increases in precipitation, more precipitation falling as rain, and increases in extreme rain events are expected to increase groundwater recharge (Crosbie and others, 2013; Zhang and others, 2016; Niraula and others, 2017; Wu and others, 2020). However, expected increases in demand for water and subsequent increases in human extraction of groundwater will decrease groundwater storage (Mrad and others, 2020). Soil moisture is expected to decrease under warming temperatures, although increases in winter and spring precipitation will seasonally facilitate high soil water content (Mankin and others, 2017; Douville and others, 2021). The hydrological status of the region's wetlands, lakes, streams, and groundwater are strongly influenced by the temporal and spatial variability of precipitation timing and intensity and regional land-use patterns (Taylor and others, 2013, McKenna and others, 2019).

Observed and projected increases in wildfire frequency and size are expected from increases in temperature (Dennison and others, 2014; Barbero and others, 2015; Donovan and others, 2017; Gao and others, 2021). The length of the fire season and duration of extreme fire weather have also been increasing (Abatzoglou and others, 2018). Fuel treatments, such as prescribed fires and grazing, are becoming increasingly important for moderating wildfire behavior and intensity in a changing climate (Rocca and others, 2014; Perkins and others, 2019; Starns and others, 2019); however, safe windows for prescribed fire are shortening and changing (Yurkonis and others, 2019).

Vegetation

Climate change impacts grassland vegetation across the North Central region in a context of altered disturbance regimes and the introduction of novel species. Species-specific responses (see, for example, Hoover and others, 2014a, b, 2019, 2021) complicate predicting shifts in composition and diversity, but novel combinations of species are highly likely (Polley and others, 2013). The Great Plains region has already experienced the fastest climate change velocity—the rate at which climate changes with respect to species' current climatic niches—of all regions in North America (Dobrowski and others, 2013). Future acceleration will expose plants to conditions changing more than 20-times faster than grass species experienced during recent periods of evolution (Cang and others, 2016). The balance between cool season (C_3) and warm season (C_4) grasses is likely to shift with climate change, which has critical implications for biodiversity, productivity, livestock forage, and wildlife habitat (Barbehenn and others, 2004; van Vuuren and others, 2006; Hoover and others, 2014a; Zelikova and others, 2014; Gherardi and Sala, 2015; Hoover and others, 2017; Winkler and others, 2019; Klemm and others, 2020). C_3 grasses are cool season grasses that use a photosynthetic pathway in which the first carbon compound produced contains three carbon atoms; C_4 grasses are warm season grasses that use a photosynthetic pathway in which the first carbon compound produced contains four carbon atoms. However, the interactive effects of climate changes and carbon dioxide (CO_2) fertilization on this aspect of vegetation are difficult to predict (Morgan and others, 1998, 2011; Mueller and others, 2016; Reich and others, 2018). Shifts in vegetation composition in response to climate change will be shaped by cooccurring changes in disturbance regimes. Interacting effects of land-use change and disturbance regimes have already facilitated an increase in woody plants in historically grass-dominated areas over the last 100 years (Allred and others, 2021). Carbon dioxide fertilization and climate-change impacts—including aridification and changing fire regimes—also promote woody encroachment into grasslands (Kulmatiski and Beard, 2013; Ratajczak and others, 2014; Gherardi and Sala, 2015; Hoover and others, 2017; O'Connor and others, 2020; Winkler and others, 2019). The most sustainable and efficient management strategy to manage woody encroachment is to minimize the initial spread of woody species into grasslands.

Predicting effects of climate change on invasive species in North Central grasslands would benefit from a clear understanding of the current extent, abundance, and composition of these grasslands. The variety of interspecific interactions that confer biotic resistance to invasive species (see, for example, Dukes 2001; van Ruijven and others, 2003; Emery, 2007; Jordan and others, 2008; Alofs and Fowler, 2013; Perkins and Nowak, 2013; Ansley and others, 2019; Allen and others, 2020) argues for the importance of maintaining high diversity of native species in all parts of the food web to reduce the likelihood of invasion as the climate changes. Plant communities become more susceptible to invasion when there is a sudden increase in unused resources (Davis and others, 2000). Such conditions are often associated with disturbances, which can be directly (drought, flood) or indirectly (land-use practices) influenced by climate change. Fire in North Central grasslands tends to have either neutral or negative effects on invasive species (Smith and Knapp, 1999; Travnicek and others, 2005; Harmoney, 2007; Ohrtman and others, 2012; Porensky and Blumenthal, 2016; Kobiela and others, 2017; Kral and others, 2018; Bennett and others, 2019; Ahlering and others, 2020; Kral-O'Brien and others, 2019; Symstad and others, 2021). Climate change effects that reduce managers' ability to conduct prescribed fires will likely exacerbate invasions in these ecoregions. Climate and CO_2 effects on the efficacy of chemical and biological control tools suggest that a greater emphasis on early detection of new threats will be critical, as will flexibility and rapid adoption of new management strategies (Ziska, 2020).

Climate change will affect the net primary productivity and timing of plant biomass production, both of which are strongly controlled by climate factors that determine the length of the growing season and the variation in water availability over that period (Fu and others, 2017). Potential increased productivity is indicated in many future climate scenarios (Reeves and others, 2014; Hufkens and others, 2016; Klemm and others, 2020), but this potential is highly dependent on changes in precipitation seasonality, vegetation composition, and the phenotypic plasticity and adaptive capabilities of plant species, all of which have high uncertainty (Mueller and others, 2016; Ficklin and Novick, 2017; Wonkka and others, 2019; Yuan and others, 2019; Knapp and others, 2020).

Grassland ecosystems in the North Central region may undergo transformation to another ecological community; however, such transformations are notoriously difficult to predict (Crausbay and others, 2022). Trajectories of ecological change are expected to be heavily influenced by management (for example, prescribed fire, grazing, and invasive species treatment). Careful, scenario-based consideration of the tradeoffs and viability of resisting, accepting, or directing change will be required (Schuurman and others, 2021).

Wildlife

As much as 15 percent of North American invertebrate and vertebrate species depend on grasslands (Poole and others, 1992; Knopf, 1996; Schneider and others, 2011; Foresman, 2012; South Dakota Department of Game, Fish and Parks, 2014; Colorado Parks and Wildlife, 2015; Dyke and others, 2015; Montana Fish, Wildlife and Parks, 2015; Rohweder, 2015; Wyoming Game and Fish Department, 2017). From mammals to arthropods, these wildlife species play important roles in the ecological processes of the central grasslands of North America. Human-caused changes to the landscape have severely decreased the extent of their range and ecological function (Ryan and others, 1998; Tscharntke and others, 2002; Batáry and others, 2012; Venne and others, 2012). Climate change will put additional stress on wildlife populations by synergistically interacting with other environmental disturbances to shift and fragment wildlife habitat and alter the timing of species lifecycles. Species with greater phenotypic plasticity will be better able to adapt to climate-change impacts, whereas species with specialized habitat requirements and limited flexibility in lifecycle timing will be at greater risk of local extirpation. We highlight the impact of climate change on *Cynomys ludovicianus* (black-tailed prairie dogs), grassland birds, fish, and arthropods. (Climate change impacts on *Bison bison* [bison] and other large grazing mammals are synthesized in the "Large-Bodied Ruminants and Grazing" section of this report.)

Cynomys (prairie dogs) played keystone roles in North America's central grasslands, but the extent of their current influence has been severely decreased (Hoogland, 2006). Despite this, they have critical roles in efforts to restore and manage these ecosystems (Davidson and others, 2012, 2018). Little is known about how climate change will shift or fragment the prairie dog ecosystem. Suitable habitat for black-tailed prairie dogs has been projected into the future under warm-and-wet and hot-and-dry climate scenarios (Davidson, Augustine, and Menefee, 2022). Additionally, the boom-and-bust population cycle caused by sylvatic plague—a nonnative disease to which prairie dogs have no natural, coevolved immunity—destabilizes the prairie dog ecosystem with cascading effects on associated species (Augustine, Dinsmore, and others, 2008; Augustine, Matchett, and others, 2008; Eads and Biggins, 2015; Keuler and others, 2020; Davidson, Augustine, and Jacobsen, 2022). The drivers of plague outbreaks are poorly understood, but seem to result from complex interactions among prairie dog colony size and densities, colony landscape characteristics, climate, and other environmental variables (Collinge and others, 2005a, b; Snäll and others, 2008; Cully and others, 2010; Davidson, Augustine, and Jacobsen, 2022). The increased frequency and duration of drought in the North Central grasslands may increase the frequency of plague epizootics with devastating consequences for species strongly associated with prairie dog "towns." Drought can also suppress reproduction and population growth rates of prairie dogs, causing colony contractions and local extinctions (Bruggeman and Licht, 2020). Competition between prairie dogs and livestock intensifies as grassland vegetation decreases (Derner and others, 2006; Miller and others, 2007; Augustine and Springer, 2013; Augustine and Derner, 2021). Trends toward or extended periods of decreased grassland vegetation productivity would result in economic stress for livestock producers and increased societal pressures against prairie dogs.

Grassland birds that breed in the North Central region are of significant conservation concern because their populations have declined the most among all habitat-based groups in North America (Rosenberg and others, 2019). Many projections for climate-based shifts in landbird distributions predict the breeding distributions for grassland birds moving northward with exceptions for sagebrush specialists (Nixon and others, 2016). Overall, grassland birds whose ranges extend into the eastern portion of the northern Great Plains, where the remaining habitat is highly fragmented and isolated, may be even more vulnerable to climate change. Increasing temperatures may lead to higher probabilities of local extinction of grassland birds in highly fragmented landscapes (Jarzyna and others, 2016). Climate change has been demonstrated to have an impact on the timing of migration and the start of the breeding season, and earlier arrival has been documented for 34 species in South Dakota and Minnesota over an approximately 35-year period (Swanson and Palmer, 2009). Other climate change risks for grassland birds include a potential mismatch in the timing of reproduction and availability of necessary food resources for raising young (Visser and others, 2006); increased conflict between human activities, such as haying and the timing of breeding season (McGowan and others, 2021); increased prevalence of disease (Marra and others, 2004; Beard and others, 2016); and the possibility of increased nest failure and mass die-offs from extreme weather and drought (George and others, 1992; Conrey and others, 2016).

Climate change is expected to significantly affect the hydrology of grassland streams and the fish that occupy them. Climate change is expected to exacerbate the physicochemical stresses prairie fishes have evolved to withstand by increasing water temperatures, reducing dissolved oxygen concentrations, increasing toxicity of pollutants through concentration, and altering hydrology (Ficke and others, 2007). The duration and extent of grassland stream intermittency are expected to increase in the face of climate change as marginally perennial streams will trend to greater intermittency, and small intermittent streams will become ephemeral (Covich and others, 1997; Datry and others, 2014). This change will result in a decrease in hydrological connectivity, suitable habitat, and water quality, whereas competition and predation will increase. Regional biodiversity and ecosystem services afforded by prairie fish are therefore expected to decrease (Jaeger and others, 2014). Although warmwater fishes may expand their ranges in some regions (Comte and others, 2013), northward habitat range shifts to accommodate changing climate are unlikely in the North Central Grassland Ecoregions, where most streams flow from the west to the east (Covich and others, 1997). Whether the shifts caused by temporal changes in temperature and discharge will be maladaptive among prairie fishes is unknown. Enhanced prevalence of disease among fishes resulting from climate change is probable (Whitney and others, 2016).

Climate change will synergistically interact with other environmental disturbances to negatively impact many arthropod species. The precise number of arthropod species across the northern Great Plains (Samson and Knopf, 1996) is likely in the tens of thousands of species and includes far more taxa with higher taxonomic levels, such as subphyla, orders, families, and genera than any other group of animals. Predicted, human-caused climate-change shifts in seasonal temperatures to earlier spring warming and later autumn cooling will cause subsequent parallel shifts in arthropod lifecycles for taxa that can adapt quickly to such changes (see Triplehorn and others, 2005; Whitfield and Purcell, 2012). More specialized species may not be able to adapt quickly to increasing temperatures and lengthening warm seasons because of their genetic inflexibility. Such species may decline and experience local extinctions. Climate change will also impact arthropods through its effects on water availability. Egg development and hatching depend on appropriate moisture conditions. Most arthropods are ultimately dependent upon plants and plant production for food, and seasonal plant production is largely dependent upon moisture availability. As overall regional ambient temperatures increase, pathogens adapted to warmer climates are predicted to move north and to higher elevations. Some disease-vector arthropods, such as ticks and mosquitoes, have already increased in numbers and expanded their geographic distribution northward in North America (Reiter, 2001; Brownstein and others, 2005; Hoy and others, 2021). Targeted geographic arthropod inventories, long-term monitoring, and experimental research are needed to adequately understand the ecologies of Great Plains arthropods, which is necessary to determine and plan for their conservation needs.

For all wildlife species, conservation in the face of climate change must incorporate consideration of socioeconomic context and policy and relevant spatial scales. Grassland wildlife priorities and outcomes in the North Central region are intrinsically tied to crop policies and socioeconomic views and values of grasslands (Drum and others, 2015). Public land use and rangeland conditions impact the availability and quality of wildlife habitat. Movement ecology and dispersal ability in a fragmented ecosystem are the main factors driving scale-dependent climate adaptation and management challenges (Allen and Singh, 2016). Managing for a suite of grassland wildlife requires the creation and maintenance of habitat heterogeneity (Fuhlendorf and Engle, 2001). Identifying where to prioritize conservation actions, such as protection, habitat reconstruction, or habitat restoration that will support current and future species' population needs is one of the greatest challenges for managing wildlife (Anderson and Ferree, 2010).

Large-Bodied Ruminants and Grazing

The impacts of climate change through warming temperatures and changes in cold and hot extremes throughout the year will have direct effects on energy budgets of large-bodied grazing species (for example, ranched bison, *Bos taurus* [cattle], *Equus caballus* [horses], *Ovis aries* [sheep], and *Cervus canadensis* [elk]) across the North Central region throughout the 21st century (Barboza and others, 2009; Martin and Barboza, 2020a, b). Rising mean annual air temperature increases energy use for thermoregulatory and metabolic functions of large-bodied grazers, which results in reduced body size (Martin and others, 2018; Martin and Barboza, 2020b). Across all mammal species, body size predicts most life-history traits, including net dietary requirements and ingestion rates, metabolic rates, growth and reproduction, and mass energy and nutrient flow (Kleiber, 1947; Peters, 1983; Damuth and MacFadden, 1990). Bison body size decreases 16 kilograms (kg) per unit of decadal mean of the Palmer Drought Severity Index, independent of mean air temperature (Martin and Barboza, 2020a); however, body mass of beef cattle has increased by 29.5 percent between 1978 and 2017 because of selective breeding (Klemm and Briske, 2021). Increased body mass during a period of warming is counter to the ecophysiological principals and laws of thermodynamics for endotherms demonstrated in bison (Martin and others, 2018).

Potential decline in the availability and changes to the nutritional quality of palatable forage will indirectly affect grazing species' growth, health, and performance (Klemm and others, 2020a, b; Martin and others, 2018). Climate change will alter the quantity and quality of forage through factors, such as changes in growing season, the timing of water availability, and plant species composition (Polley and others, 2013). Elevated CO_2 is expected to increase the total amount of forage available but could result in lower quality forage for grazers (Dumont and others, 2015; Belesky and Malinowski, 2016; Augustine and others, 2018, 2020). Greater year-to-year variability in precipitation, combined with warming, will lead to greater fluctuation in grassland forage production (Briske and others, 2020; Espeland and others, 2020; Klemm and others, 2020b). Projected decreases in growing season water availability and increases in drought stress will increase nutritional stress for animals, resulting in increased disease, slower growth, and increased mortality for large-bodied ruminants. Although exposure to various direct and indirect effects of climate change (warming, drought, and effects on forage quality and quantity, animal health, and performance) may be similar across the North Central grasslands, sensitivity and adaptive capacity will vary geographically across land jurisdictions and management sectors, such as public, NGOs, Tribal, and private stakeholders (Wilmer and others, 2018; Martin and others, 2021; Pejchar and others, 2021; Shamon and others, 2022). There are several ways to reduce the impacts of climate change on grazing, including converting marginal cropland back to perennial grasslands, increasing plant diversity, and planting nutritious forbs in existing grasslands (Lupo and others, 2013; Miller, 2013). The current rate of change of Earth's climate is without historical reference in at least the last 3 million years, creating extinction risks for many grassland forage species (Zeebe and others, 2016; Hayhoe and others, 2017). Assisted migration may be required to ensure sustained forage production (McLachlan and others, 2007; Mueller and Hellmann, 2008; Bucharova, 2016).

Land-Use Change

Changes in land use are driven by complex interactions between the availability of biophysical resources and socio-economic factors, both of which will be impacted by climate change (Drummond and others, 2012; Conant and others, 2018; Intergovernmental Panel on Climate Change, 2019; Bentley Brymer and others, 2020; Doidge and others, 2020; National Academies of Sciences, Engineering, and Medicine and others, 2021). Across the North Central grassland ecoregions, land is used for numerous purposes including agricultural uses, such as livestock grazing and cropping; energy development; and urban, suburban, and exurban development. Most grasslands in the region are privately owned, which means that Federal, State, Tribal, and nonprofit organizations and agencies cooperate with private landowners to conserve grassland habitat and prevent grassland conversion to other uses (Miller Hesed and Yocum, 2023).

Climate change will impact which areas are suitable for grazing or growing certain row crops, which areas may be converted to another use—for example, from grazing to row crops, from row crops to grazing, or from one row crop to another—and which areas could be prioritized for restoration. Across the North Central region, some areas will become more suitable for grazing, whereas others will become more suitable for cropping (Ojima and others, 2002; Wick and others, 2016; Hsiang and others, 2017; Conant and others, 2018; Arora and others, 2019). In places where the biophysical suitability for grazing shifts only marginally, socioeconomic factors will likely play a large role in determining whether those areas continue to be grazed and how intensely they are used (Ojima and others, 2002; Reeves and others, 2018); in areas where climate change may result in more favorable conditions for row crops, rangeland and the livelihoods and habitats they can support may be lost. This loss has implications for grassland habitat and grassland-dependent species because sustainably managed rangelands can protect biodiversity, provide additional ecosystem services such as carbon storage, and provide economic benefits to landowners and rural communities (Shortridge, 2003; Brunson and Huntsinger, 2008; Sullivan, 2009; Goldstein and others, 2011; Wick and others, 2016; Augustine and others, 2019; U.S. Department of Agriculture, 2019; Maher and others, 2021; Richter and others, 2021).

The profitability of row crops—such as wheat, corn, and soy—has been a primary driver of grassland loss and agricultural conversion in the North Central region since European colonization (Conant and others, 2018; Doidge and others, 2020; Ott and others, 2021; World Wildlife Fund [WWF], 2021; South Dakota's Conservation Districts, 2022). Changes in temperature and precipitation will alter the areas of the North Central region that are suitable for specific crops (Kunkel and others, 2013; Ballard and others, 2014; Hsiang and others, 2017; Tollerud and others, 2018; Arora and others, 2019). As the climate continues to change, there is increasing interest in genetically modified crops that can withstand extreme events and projected changes in temperature and precipitation (Moser, 2010; Chen and others, 2015; Tollerud and others, 2018; Rising and Devineni, 2020). The prevailing driver of grassland conversion is the profitability of cropland relative to other uses (Claassen and others, 2011; Dinterman and Katchova, 2019; Doidge and others, 2020; Lark, 2020); however, nonmarket factors, including lifestyle choice and stewardship perspectives, can be more important determinants of land-use decisions than economics and can act to slow the rate of rangeland and grassland conversion to cropping or other uses (Bruno and others, 2020; Doidge and others, 2020).

The energy sector in the North Central region is changing because of economics and public policy aiming to reduce carbon emissions (Conant and others, 2018; Kloesel and others, 2018; Koebrich and others, 2018; Zamuda and others, 2018; U.S. Department of Energy, 2021; Energy Information Administration, 2022). Wind-energy development is the energy sector most likely to grow in the North Central region in the coming decades (Hoen and others, 2018; Koebrich and others, 2018; Ott and others, 2021; U.S. Geological Survey, 2022). Wind-energy development an important contributor to the decarbonization of the energy sector (Edenhofer and others, 2011; Intergovernmental Panel on Climate Change, 2019), but it can fragment and degrade grassland habitats and lead to increased mortality for birds, bats, and other species (Forrest and others, 2004; Ceballos and others, 2010; Wick and others, 2016; Rottler and others, 2018; Ott and others, 2021); however, these impacts can be mitigated by carefully selecting sites for wind turbines to reduce environmental impacts on grassland habitats and species (Shaffer and Buhl, 2016; TNC, undated; Hise and others, 2022).

Urban, suburban, and exurban development has increased in the North Central region since the 1950s and continues to lead to grassland loss, fragmentation, and degradation (Theobald and others, 1996; Brown and others, 2005; Drummond and others, 2012; Reeves and others, 2018). Development and related infrastructure affect grassland-dependent species differently and their effects can extend far beyond the footprint of the infrastructure itself (Klug and others, 2010; Beckmann and others, 2012; Riley and others, 2012; South Dakota Game, Fish and Parks, 2014; Thompson and others, 2015; Rodgers and Koper, 2017; Sawyer and others, 2017; Reeves and others, 2018). Increased urban, suburban, and exurban development may also affect local temperature, water availability, and fire regimes by trapping heat, increasing runoff, and increasing the risk of fire-related hazards (Abatzoglou and others, 2018; Sleeter and others, 2018).

Conservation of grasslands is a shared goal for many Federal, State, and Tribal grassland managers and is a key land use in the region (Miller Hesed and Yocum, 2023; Baier, 2020; Pittman and Ayambire, 2022; WWF, 2020). As climate-driven changes in precipitation and temperature impact agriculture, it may be possible to identify lands that are no longer optimal for row-crop agriculture and target them for restoration or conversion to sustainable grazing land, which can benefit grassland species and rural communities.

Remaining Research Needs

The synthesis of existing climate and ecology research findings presented in this report addresses many of the information needs identified in the first report of this Grasslands Synthesis Project; however, there remain a number of research gaps. First, synthesizing research in the social sciences was outside the scope of this report, but will be necessary to address grassland managers' broadly shared information needs. Second, the North Central Grassland Ecoregion is home to 27 federally recognized Native American Tribes with traditional ecological knowledge. Collaboration with Tribal members and integration of scientific and traditional knowledge could help to inform successful grassland management in the face of climate change. Third, through our review of the climate and ecology literature, we note that there are gaps in the existing information, and that research is needed to:

1. Refine spatial and temporal analyses for future changes in temperature, precipitation, and drought, and improve understanding and quantification of extreme weather patterns and events;

2. Improve understanding and predictions of changes in hydrology, streamflow, and soil moisture for actionable management adaptations;

3. Study interactions among invasive species, fire, CO_2, warming, drought, woody encroachment, grazing, and climate to improve predictions of climate change outcomes for plant community composition and wildlife habitat;

4. Assess and understand current status, future trends, and climate-related risks for plant and animal species populations across the region;

5. Investigate sustainable grazing management practices that are adaptive to changes in forage quality across varying spatial and temporal scales; and

6. Identify and map existing native grasslands, unplowed areas, and successful prairie reconstructions.

Finally, collaboration between researchers and grassland managers in developing future research projects will ensure that the information gained will be relevant, accessible, and usable for informing climate-smart management decisions.

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