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Recent Climate Changes Across the Great Plains and Implications for Natural Resource Management Practices☆

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ABSTRACT

The Great Plains region plays an important role in providing water and land resources and habitat for wildlife and livestock, crops, energy production, and other critical ecosystem services to support rural livelihoods. The semiarid conditions of the region and tight coupling of livelihood enterprises with ecosystem services creates a situation of increased sensitivity to climate changes and enhanced vulnerability among the rural communities and Native American nations across the region. Recent climate conditions associated with warming trends, and altered atmospheric flows have resulted in rapid onset of drought conditions and other extreme weather events across the region that are changing seasonal patterns of temperature and precipitation and warming trends. Projected climate changes provided in the fourth US National Climate Assessment indicate that potential warming and variability of precipitation will further increase drought and extreme weather events.

Recent research and assessment efforts of current and projected climate changes in the Great Plains indicate that rural communities and ecosystems are becoming more vulnerable to changes associated with warming trends, droughts, and increased variability in precipitation. These climate changes are having differential impacts on ecosystem services that are critical to livelihood enterprises. Strategies for how resource managers and the research community can better collaborate and more effectively codesign and coproduce efforts to understand and to respond to these challenges are needed.

Introduction

The Great Plains (GP) region plays an important role in providing water and land resources and habitat for wildlife and livestock, crops, energy production, and other critical ecosystem services to support rural livelihoods. The land use coverage supporting rural livelihoods is dominated by semiarid ecosystems, such as grasslands, shrublands, and dryland agriculture (Fig. 1). Climate change is affecting the natural resource base supporting enterprises associated with ranching, crop agriculture, conservation, and recreation (Ojima et al. 2015; Even and Ojima 2019). Reliance on the availability of ecosystem services and other natural resources in this semiarid region to support rural livelihoods forms a basis of a social-ecological system that links climate change, availability of ecosystem services, and socioeconomic and cultural characteristics operating across the region. Recent and projected climate changes across the GP are affecting drought events, extreme weather patterns (e.g., ice storms, hot spells, out-of-season frost events), flooding, and fire occurrences (Ojima et al. 2015).

The region's socioeconomic system is characterized by extensive rural population density with a recent concentration of population growth in urban areas. As of 2010, there were almost 42 million people (≈13% of the total US population) living in the nine US GP states, including Colorado (USDA Economic Research Service 2012). The average population density over the region is about 66 people per square mile, with a median of 10 people per square mile (US Census Bureau 2010). Although the region's overall

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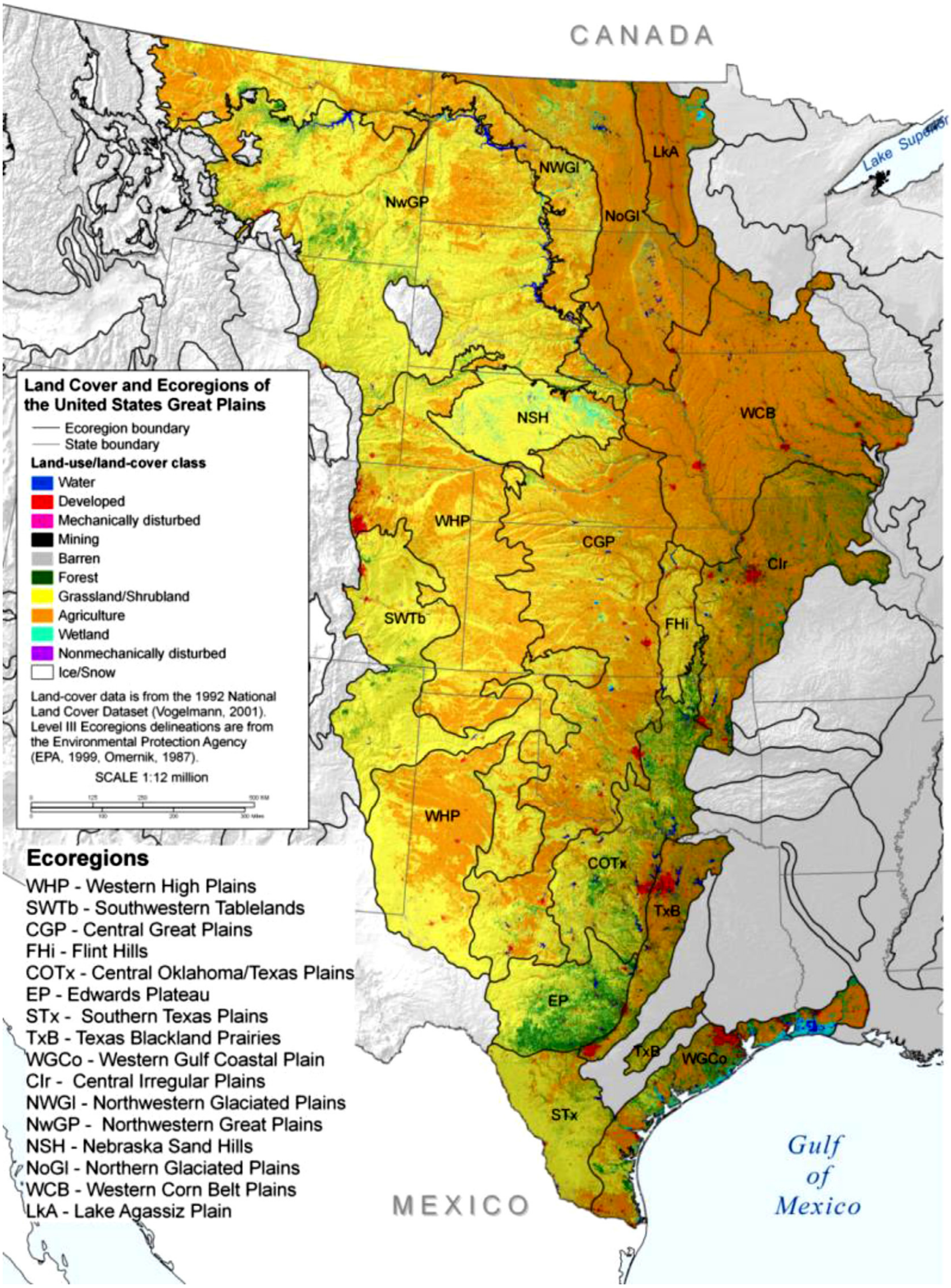

Fig. 1. Land cover map of the Great Plains region of the United States (Ojima et al. 2015).

population has been increasing, the growth has not been equitable across counties. Urban population numbers have grown to almost 33 million persons in 2010 (US Census Bureau 2010), whereas 39% of the counties in the GP have declined in population from 1990 to 2010 (US Census Bureau 2010). Rural counties are much more likely to lose population than those with urban development.

Native American tribes and communities also represent a critical population and cultural heritage in the GP. Native American tribes number approximately 65, managing extensive land, water, and wildlife resources. Reservation lands are often marginal and less productive with limited access to fertile soils; inadequate water resources, social services, and infrastructure; and limited food security. There are about 450,000 persons claiming Native American ethnicity according to the US census data (US Census Bureau 2000, 2010).

The semiarid climate conditions and interannual variability driven by synoptic-scale atmospheric flows contribute to the varied weather patterns of the region. These conditions contribute to droughts; changing seasonal climate patterns affecting snow melt; altered seasonal stream flows; earlier green-up of the vegetation;

Table 1
Average changes in temperature (units in °C) characteristics of the period 1986–2016 compared with a historical base period of 1901–1960 over the northern and southern portions of the Great Plains. (Source USGCRP 2017.)

Great Plains region	Change in annual average temperatures	Change in annual average maximum temperatures	Change in annual average minimum temperatures
Northern Great Plains	+0.94°C	+0.92°C	+0.96°C
Southern Great Plains	+0.42°C	+0.31°C	+0.53°C

and extreme events such as fires, ice storms, and floods affecting ecosystem services (e.g., forage and browse availability, soil moisture, habitat, water availability) in time and space. Livelihood strategies have evolved to the availability of ecosystem services and variable weather patterns so that recent and projected climate changes in the region result in greater uncertainty. The increased weather variability and extreme events are also contributing to enhanced vulnerability of rural communities (Marshall et al. 2014; Shafer et al. 2014; Even and Ojima 2019) and Native American communities across the region (Eiser et al. 2012; McNeeley 2017; Jantarasami et al. 2018).

This paper describes recent atmospheric conditions contributing to climate changes affecting weather patterns of the region. Future climate projections based on the US Fourth National Climate Assessment (fourth NCA) report (USGCRP 2017) are presented to provide a perspective of how these changes will manifest themselves into the future. The manner in which recent climate changes affect droughts, fires, and extreme events is discussed. Examples are provided of how natural resource managers are responding to these climate changes. We conclude the paper with a discussion of framing adaptation planning within a social ecological system perspective that enables the development of adaptive management strategies that incorporate aspects of adaptive capacity of a particular livelihood and to better target management options.

Trends in Recent Climate Patterns and Controls Across the Great Plains

Recent US National Climate Assessment reports (Kunkel et al 2013; USGCRP 2017) provide information on current trends of weather and climate conditions across the United States and GP. In addition to warming trends reported in the fourth NCA (Kunkel et al. 2013; USGCRP 2017), certain features of the GP climatology are changing and resulting in changes of weather patterns and extreme events of the region (USGCRP 2017). These include changes in the controls of arctic air mass flow across the northern hemisphere with the warming of the arctic ocean; changes in snow amounts and timing; and rapid warming of the atmosphere during the growing season (Conant et al. 2018). The changes in various climate controls are reflected in recent observations of extreme weather events across the GP (Kunkel et al. 2013; Peterson et al. 2013; Conant et al. 2018; Kloesel et al. 2018).

Climate in the region is strongly connected to the topography of the Rocky Mountains, influence of arctic jet stream, and water vapor inputs from the Pacific Ocean and Gulf of Mexico (Rosenberg 1987; NOAA 2013). In addition, the expansive north-south extent of the GP allows for a strong temperature gradient to exist that gets warmer as one moves southward. From 1986 to 2016, the northern GP has experienced a warming of about 0.9°C and the southern GP has had an approximately 0.4°C increase in mean annual temperatures (USGCRP 2017; Table 1).

Precipitation across the GP has a distinct west-to-east gradient with greater precipitation occurring annually as one travels eastward (Rosenberg 1987; Shafer et al. 2014). Annual average precipitation ranges from 200 mm in the west to approximately 1 100 mm in the east and southeastern portion of the region and is highly variable from year to year. There has been a small overall change in mean annual precipitation levels of the same time period (1986–2016 period compared with the complete 20th century record; USGCRP 2017). In addition, extreme weather events, such as droughts, floods, tornadoes, hail, ice storms, heat waves, and blizzards, in the GP are common. Also, along the southern extent of the GP hurricanes occur.

Winter weather patterns across the GP are associated with the arctic jet stream that, in combination with Pacific air masses, determine the extent and amount of snowfall, occurrences of ice storms, and cold temperature extremes (Rosenberg 1987; NOAA 2013). The arctic jet stream influences winter conditions over the GP, bringing cold arctic air masses with the jet stream. The exposure to the arctic jet stream dipping into South Dakota and farther into Colorado and Kansas can lead to severe winter storms. These can also lead to ice storms and, as experienced in Oklahoma, snow transitioning to rain in the southern GP. These winter storms have an extensive impact on livestock, transportation, power lines, and human safety (Shafer et al. 2014; Ojima et al. 2015).

Overall, cold weather extremes in the region have become less severe over the past century (USGCRP 2017). In the northern portion of the GP the average coldest day temperature has risen by 2.44°C and the southern portion by 1.81°C (USGCRP 2017, extracted from Table 6.2). However, in the past decade severe winter events have emerged due to the warming of arctic region and the effect of the weakening of the polar vortex on the movement of cold air masses into the interior of the North American continent (Kolstad et al. 2010; Kretschmer et al. 2018). Over the past decade these cold air excursions have resulted in extreme cold temperatures throughout the GP.

The GP is also prone to extreme snowstorms, especially in the northern and central portions of the region. For example, the exposure to the jet stream dipping deeply into South Dakota and as far south as Colorado and Kansas during the fall of 2013 led to a heavy snowstorm, referred to as the *2013 Atlas Storm*. As much as a meter of snow fell between October 3 and 5 in the area adjacent to the Black Hills of South Dakota (National Weather Service 2013). The Atlas Storm was responsible for the loss of 1 000s of head of cattle and other livestock. The early October timing of the storm contributed to the heavy loss of cattle since the livestock had yet to put on their heavy winter coats (NWS 2013).

The transition between spring and summer seasons can result in turbulent weather patterns with increased moisture emerging from the Gulf of Mexico and as cold air descends from the Rocky Mountains, contributing to upslope snow dynamics in the spring and monsoon-like rainfall in the summer. Growing season rainfall and humidity levels are controlled by a complex set of factors, which include the El Nino-Southern Oscillation dynamics, the Pacific Decadal Oscillation (Chen et al. 2017), moisture flow from the Gulf of Mexico (Higgins et al. 1997; Algarra et al. 2019), and the GP lower-level jet (GPLLJ) dynamics in connection with mesoscale convective systems (MCS) that create stationary convective systems, which tend to concentrate rainfall (Schumacher and Johnson 2006; Squitieri and Gallus 2016). Recent studies have found that large regions of the central United States are showing upward trends in April–June MCS rainfall of approximately 20–40% per decade from 1979 to 2014 (Feng et al. 2016). Analyses of the spring and summer rainfall patterns are critical predictors of forage production in rangelands across the region (Chen et al. 2019).

During the spring to summer transition, unstable atmospheric conditions may occur due to strong differences in moisture levels and air temperatures in rather short periods of time that can lead to extreme convective storms and tornados (Boustead et al. 2013; Chu et al. 2019). A variety of atmospheric conditions can lead to these extreme storm and tornado events, including warm dry air masses moving across the southwest, warm moist air intrusions from the Gulf of Mexico, and the relatively cold air mass associated with the arctic jet stream (Boustead et al. 2013; Chu et al. 2019). In May 2007, nearly 95% of Greensburg, Kansas, was completely destroyed by an EF5 tornado and 11 lives were lost. The event was part of a larger-scale tornado outbreak over a four-state region throughout the Plains.

Hurricanes and tropical storms penetrate the GP from the Gulf of Mexico and Caribbean (USGCRP 2017; Kloestel et al. 2018). The effects of hurricanes can extend well beyond the immediate coastal areas, and the remnants of hurricanes will track northward and westward into the interior of the GP. Such storms have caused heavy rainfall events from interior Texas to as far north as Nebraska (Knight and Davis 2009).

In addition to these intense convective systems and tornados, heat accumulation in the plains is associated with high humidity levels that can lead to heat-stress events. These events can be lethal to people (McGeehin and Mirabelli 2001) and livestock (Mader 2003). The heat wave and drought of the summer of 2011 across the southern portions of the GP region had major impacts on human livelihoods, crops, livestock, water supplies, and wildlife (Ojima et al. 2015).

Extreme rainfall events in the region can trigger flooding events. These events have been associated with mesoscale convective systems (Schumacher and Johnson 2006; Danco and Martin 2018), which result in the concentration of rainfall over a particular region contributing to flooding conditions. An active GPLLJ is responsible for moisture flow from the Gulf of Mexico into the interior of the GP and accounts for $>$ 50% of the precipitation across the region (Schumacher and Johnson 2006; Danco and Martin 2018). These conditions reflect the temporal characteristics of episodic rainfall events associated with tropical depressions in the Gulf of Mexico, nocturnal development of the GPLLJ, and high-pressure blocking systems in the eastern United States (Higgins et al. 1997; Lavers and Villarini 2013) resulting in high-intensity rainfall events and flooding. These spring-time events can have a larger regional impact, especially when spring snowmelt coincides with frontal weather patterns providing rainfall across an area with saturated soils. These conditions contributed to the 2011 floods along the Missouri River and 2019 flooding in the central United States. During the past decade, a number of meteorological events have contributed to the floods across the GP including early snowmelt, precipitation on already saturated soil profiles, rain on partially thawed soils with existing frozen soil layers near the surface, and recent “bomb cyclones” delivering high levels of precipitation in an area (Higgins et al. 1997; Lavers and Villarini 2013).

Droughts are not uncommon in the GP, as noted by the 19th century explorer Major Stephen H. Long in describing the region as the “Great American Desert.” Droughts across the GP are frequent events, and the region has experienced multiyear droughts in the mid 1800s (Rosenberg 1987; Woodhouse et al. 2002). These droughts are associated with high temperatures or by lack of rainfall, or both, working in concert with each other (Rosenberg 1987; Woodhouse et al. 2010). Conditions that block moisture from flowing up from the Gulf of Mexico can result in drought conditions as in 2006 (Dong et al. 2011). The 2011 drought in Texas and the southwest region of the GP was one of the most intense droughts "in the recorded history available to NOAA (NOAA 2012).

Recent drought events (e.g., 2012, 2015, 2017) are presenting novel features and challenges due to the rapid onset of drought conditions in areas where soil moisture conditions appeared to be suitable for forage production in previous years (McNeeley et al. 2017b; Gerken et al. 2018; Otkin et al. 2018). As the growing season progresses, air temperatures rapidly increase, leading to higher levels of atmospheric evaporative demand and a rapid withdrawal of soil moisture (Hobbins et al. 2016; Dewes et al. 2017; Hoell et al. 2018; Otkin et al. 2018). These drought conditions occur suddenly and are referred to as “flash droughts” (Hobbins et al. 2016). Due to the rapid onset and relatively good soil moisture before the increased evaporative demand, these droughts are more difficult to forecast with current long-term or seasonal forecasts (Hobbins et al. 2016). The flash droughts during the past decade (i.e., 2012 to present) have resulted in loss to cattle and dryland cropland production.

Seasonal changes in warming trends in the late winter and spring seasons are changing snow melt and stream flow from the mountains and into the plains (Fassnacht et al. 2016; Gross et al. 2016; McNeeley 2017). For instance, in the northern GP average runoff during the period between 2000 and 2010 displayed a marked decrease, though precipitation levels were essentially unchanged, suggesting that the increased growing season warming resulted in an increase in evaporative demand reducing overall runoff (Griffin and Friedman 2017; Martin et al. 2020).

Projected Climate Changes for the Great Plains

Analyses of projected climate changes have been conducted with an ensemble of coupled atmosphere-ocean global circulation models (AOGCMs) under the guidance of the Coupled Model Inter-comparison Project Phase 5 (CMIP5; Hibbard et al. 2007; Moss et al. 2008) for the Intergovernmental Panel on Climate Change Fifth Assessment (IPCC 2013). Under the CMIP5 protocol, various projected climate scenarios were simulated under specified radiative forcing of the atmospheric using a number of AOGCMs representing atmospheric warming levels at 4.5 W/m^2 and 8.5 W/m^2 (van Vuuren et al. 2011) and are denoted as RCP 4.5 and RCP 8.5, respectively. The Fourth US National Climate Assessment used these model results for the United States to assess future projected changes across regions and economic sectors in the United States (USGCRP 2017). Climate change projections for the GP are derived from a subset of CMIP models used by the AdaptWest Project (Wang et al. 2016). Results of the changing climate on the GP in the northern region and southern region are summarized here.

Warming trends throughout the region are expected to continue (Table 2). Consistent with observations of mean annual temperature changes over the northern and southern tiers of the GP, the north is projected to experience more warming over the coming decades, ranging from 2.7°C to 3.5°C in the 2050s and 3.1°C to 5.4°C in the 2080s with the higher warming levels associated with higher emission scenarios (RCP 8.5) (see Table 2). The southern region is projected to have a similar changes in annual temperatures, ranging 2.1°C to 2.9°C in the 2050s and rising to 2.6°C to 4.8°C in the 2080s (see Table 2). The lower change is related to the higher baseline annual temperatures experienced in the southern GP. Regional changes in mean annual temperature projected over the northern and southern regions indicate similar changes in annual warming trends (Fig. 2).

Projections of precipitation are highly variable across the region though ensemble mean differences from historical mean annual precipitation suggests a reduction in average annual precipitation over both emission scenarios. Regional precipitation changes for the northern region are projected to decrease slightly with a decrease of 7.0−7.9 mm in the midcentury mean annual difference and a decrease of 7.5 mm with the RCP 4.5 scenario and 0.63-mm decrease with the RCP 8.5 scenario at the end of century (Table 3). There appears to be west to east decline in precipitation,

Table 2
Projected changes in annual average temperature (°C) for National Climate Assessment Great Plains regions, northern and southern portions. Changes are the difference between the average for midcentury (2041–2070) or late-century (2071–2100) and the average for near-present (1981–2010) under the lower scenario (RCP4.5) and higher scenario (RCP8.5). Values included in parentheses represent the highest and lowest values within the subregion at each time point (i.e., the highest and lowest values within each subregional selection of the dataset). Estimates are derived from WorldClim and PRISM historical climate data and a 15-model subset of the CMIP5 model array selected for their representativeness across the major model families of the CMIP process and interpolated 1-km gridded current and projected climate dataset, a publicly available set of spatial rasters designed to highlight potential climate change in the North American continent (AdaptWest Project 2015).

		RCP4.5	RCP8.5	RCP4.5	RCP8.5
Great Plains region	Recent 30-yr normal (1981-2010)	Midcentury (2041-2070)	Midcentury (2041-2070)	Late century (2071-2100)	Late century (2071-2100)
Great Plains North	8.67°C	+2.68°C (1.11-2.68°C)	+3.34°C (2.08-3.44°C)	+3.08°C (1.71-3.48°C)	+5.44°C (3.49-5.77°C)
Great Plains South	17.3°C	+2.06°C (0.85-2.70°C)	+2.87°C (1.77-3.57°C)	+2.61°C (1.22-3.66°C)	+4.79°C (3.49-5.83°C)

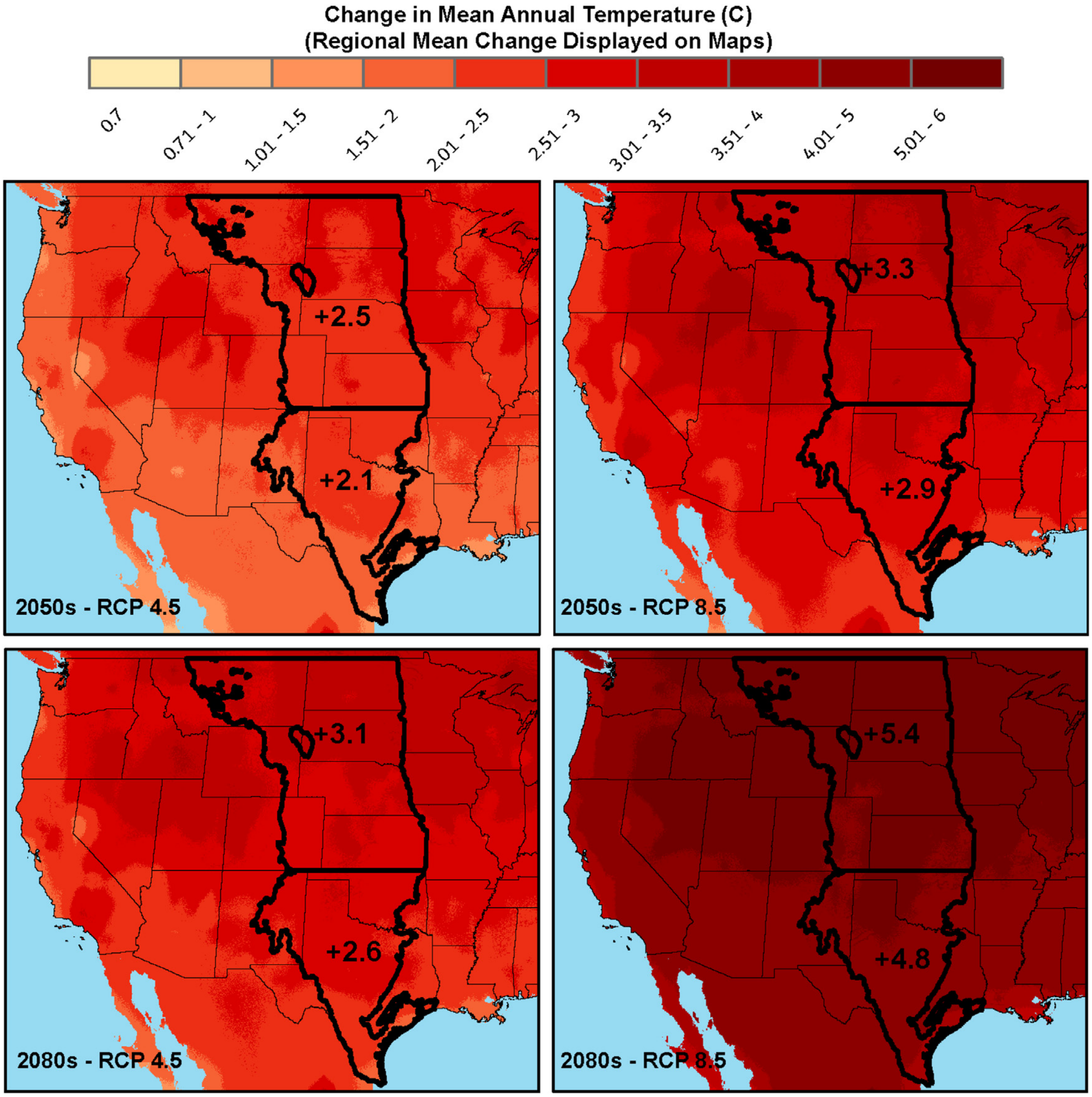

Fig. 2. Projected mean annual temperature changes (°C) under RCP 4.5 and 8.5 for mid-century (i.e., 2035 to 2065) and end of century (i.e., 2070 to 2100) time period. Values in each region represent the averaged change value derived from the 1km downscaled 15 model ensemble used in the Adaptwest project. (Available at: http://adaptwest.databasin/adaptwest-climatena; Wang et al. 2016).

with an increase in the western portion and a slight drying out in the eastern portion (Fig. 3).

The southern portion of the GP is projected to have a decrease in mean annual precipitation ranging from −29.6 to −47.9 mm, RCP 4.5 and 8.5, respectively (see Table 3). Projections for the southern region suggest more severe reductions in precipitation in the eastern portion of the southern GP, with the southwest portion of Texas projected to experience a slight increase in precipitation (see Fig. 3).

Seasonal changes in precipitation vary between the northern and southern portions of the GP (USGCRP 2017). The northern GP are projected to be wetter in the winter and spring seasons by 2100. The southern GP in winter and spring are projected to have decreased seasonal precipitation levels. The summer and fall seasons throughout the GP are projected to have less precipitation. The southern GP is projected to experience approximately 5–15% less summer precipitation compared with the average summer precipitation occurring during the period 1976–2005

Table 3
Mean annual precipitation (in mm) changes over northern and southern regions of the Great Plains. Changes are the difference between the annual average values for midcentury (2041–2070) or late century (2071–2100) and the average for near-present (1981–2010) under the lower scenario (RCP4.5) and higher scenario (RCP8.5). Values included in parentheses represent low and high values from within each subregion at each time point (i.e., the highest and lowest grid cell values for each selection of the dataset). Estimates are derived from WorldClim and PRISM historical climate data and a 15-model subset of the CMIP5 model array selected for their representation across the major model families of the CMIP process and interpolated to a 1-km grid. (Source: AdaptWest Project 2015.)

		RCP4.5	RCP8.5	RCP4.5	RCP8.5
Great Plains region	Recent 30-yr normal (1981-2010)	Midcentury (2041-2070)	Midcentury (2041-2070)	Late century (2071-2100)	Late century (2071-2100)
Great Plains North	508 mm	−6.95 mm (−109 mm to +182 mm)	−7.82 mm (−108 to +190 mm)	−7.53 mm (−116 to +192 mm)	−0.63 mm (−104 to +232 mm)
Great Plains South	679 mm	−22.42 mm (−141 to +67 mm)	−33.69 mm (−168 to +58 mm)	−26.09 mm (−144 to +66 mm)	−46.61 mm (−209 to +55 mm)

(USGCRP 2017). The summer reduction in precipitation and the warmer projected temperatures in the region suggest higher evaporative demand and a decrease soil moisture levels leading to greater drought conditions (USGCRP 2017).

Projected impacts of these climate changes include an increase in the number of extreme hot days by 2100 across the GP (USGCRP 2017). In the northern region, where precipitation as snow is important to soil moisture recharge and streamflow dynamics, the amount of precipitation falling as snow is projected to be reduced by 25−40% by 2100 (USGCRP 2017; Conant et al. 2018). Snowmelt is projected to occur earlier in the spring and result in higher flow levels earlier in the water year. Water management will be challenged by changes in earlier streamflow pattern and warming trends in the growing season, which will lead to greater evapotranspiration and soil moisture deficits (Ojima et al. 2015; McNeeley et al. 2016).

Implications of Climate Change on Natural Resources Management Strategies

Climate change is already impacting natural resources and ecosystem services (e.g., land productivity, water availability, seasonal dynamics of ecosystem and wildlife dynamics) and is expected to continue to exacerbate these effects on ecosystems, wildlife, other natural resources, and human livelihoods in the GP region (Ojima et al. 2015; Conant et al. 2018; Kloesel et al. 2018). Recent climate change impacts include a reduction in the snow season (e.g., later onset in the fall and earlier melt in spring) changing the amount and timing of streamflow; reduced soil moisture during the growing season; earlier green-up of vegetation; an increase in evaporation (leading to evaporative stress on the landscape and more frequent and severe drought conditions); and an increase in extreme precipitation events leading to increased risks of flooding and erosion (Ojima et al. 2015). These changing weather conditions have contributed to droughts in 2000, 2012, 2015, and 2017; fire events in the GP during the 20 yr (Donovan et al. 2017; Lindley et al. 2019); flooding and extreme storm events across the GP; and pest outbreaks. These recent events provide insights of how climate change may affect natural resources and impact natural resource management that support livelihoods across the region (Ojima et al. 2015; Conant et al. 2018; Kloesel et al. 2018).

Although communities across the region have adapted to regional climate conditions, the magnitude, speed, and increased variability of weather events can exceed the coping capacity of managers across sectors in the region (Shafer et al. 2014; Conant et al. 2018). A series of climate impact and adaptation studies provides insights into how various natural resource managers have responded to recent drought events (Kachergis et al. 2014; Yung et al. 2015; Derner and Augustine 2016; McNeeley et al. 2016; Shafer et al. 2016; McNeeley et al. 2017a). These studies incorporated social-ecological system approaches that included enhanced dialogue between researchers and managers that improved the analysis of socioeconomic factors across a range of management options. These approaches aided in the development of actionable adaptation strategies across a variety of rural livelihood operations. Social and institutional structures also influence decision making and determine constraints or opportunities to adaptation planning (Adger et al. 2005; West et al. 2009; Travis 2014). Institutional responses to climate change are often best suited for mitigation of emergency situations and isolated events rather than for slower-onset, cumulative, or systemic climate-related problems leading to disruption of ecosystem services (Adger 2006; Adger et al. 2005; Travis 2014; Barnett et al. 2015).

In rural and Native American communities of the GP, many social services (e.g., school systems, Internet access, medical services, delivery of drinking water) have been greatly diminished and mechanisms to enable sufficient planning processes and implementation actions are lacking (Ojima et al. 2015; McNeeley 2017; Jantatasami et al. 2018). Emerging efforts with US Department of Agriculture, National Oceanic and Atmospheric Administration, and Department of the Interior agencies are attempting to codevelop adaptation plans in these rural and Native American communities (Steiner et al. 2015; Shafer et al. 2016; McNeeley et al. 2017b; Averyt et al. 2018; Hanberry et al. 2019).

The following examples associated with droughts, fires, and flooding events are provided to illustrate the consequences of climate change effects on natural resources and ecosystem services and to provide a perspective of the evolving management strategies in response to changing weather patterns. These examples are not meant to be comprehensive guides but rather representative of actions taken for adaptation planning to these events.

Droughts

As indicated in the previous section, droughts are a natural occurrence across the GP; however, recent events and future projections of climate conditions indicate a more rapid onset of drought. In addition, land use changes, reduced access to social services, declining availability of groundwater resources, and changing climate conditions are contributing to increased exposure and impacts to droughts across the region (Steiner et al. 2015; Derner and Augustine 2016; Hanberry et al. 2019). Communities across the GP are faced with an aging and often less efficient infrastructure for water management under drought conditions. Native American communities are especially affected by recurring drought events due to lack of clarity of water rights, the lack of federal support to maintain and repair irrigation systems, and inadequate water management infrastructure on Native American reservations in the GP (McNeeley 2017; McNeeley et al. 2017b; Jantarasami et al. 2018).

The rural livelihoods and conservation practices used to maintain livestock, wildlife, and natural resources in the region are also being impacted by these droughts. The impact of the 2012 drought indicated that cattle and wheat productivity were greatly reduced

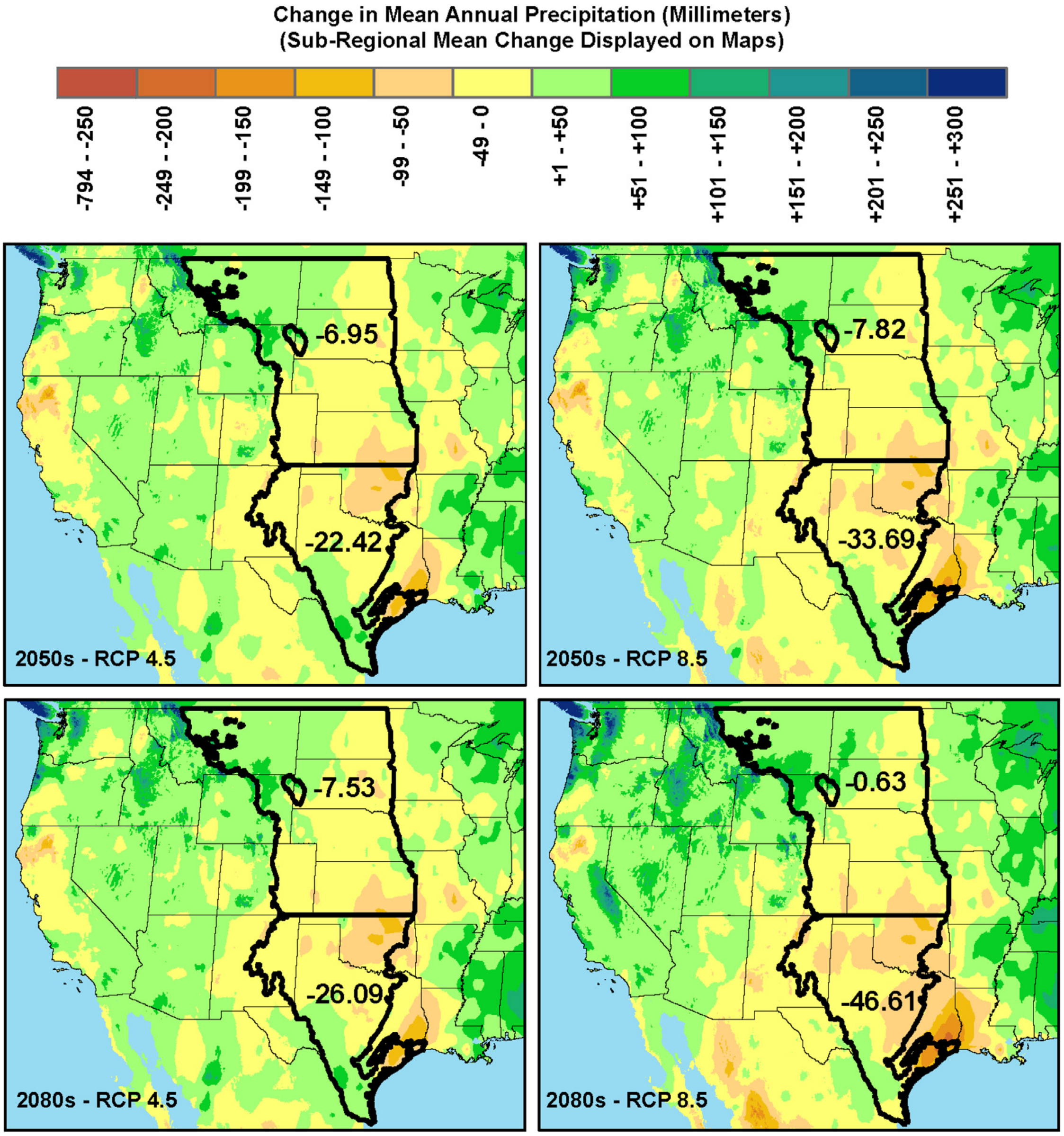

Fig. 3. Projected mean annual precipitation changes (°C) under RCP 4.5 and 8.5 for mid-century (i.e., 2035 to 2065) and end of century (i.e., 2070 to 2100) time period for northern and southern Great Plains regions. . Values in each region represent the averaged change value derived from the 1km downscaled 15 model ensemble used in the Adaptwest project. (Available at: http://adaptwest.databasin/adaptwest-climatena; Wang et al. 2016).

with up to 75% of the cattle inventory nationwide exposed to the 2012 drought conditions (Rippey 2015). Wildlife were affected by the drought 2012 in areas such as Wind Cave National Park, Badlands National Park, and the Pine Ridge Reservation with loss of buffalo and other wildlife due to reduced forage and surface water resources (McNeeley et al. 2016).

Adapting to drought is a major regional challenge faced under climate change, leading to various state and federal actions to support adaptation planning and capacity-building (Steiner et al. 2015; Shafer et al. 2016; McNeeley et al. 2017a; Hanberry et al. 2019). These state and federal agencies have undertaken supporting research and engagement activities that have included integrated research efforts and management planning exercises between multiple agencies and entities (Steiner et al. 2015; McNeeley et al. 2016; McNeeley et al. 2017b; Beeton et al. 2019). For example, a joint effort led by tribal water managers at the Wind River Indian Reservation of Wyoming with partners from the USGS, NOAA, US Department of Agriculture, and several universities (i.e., Colorado State University, University of Colorado–Boulder, University of Nebraska–Lincoln, and University of Wyoming) has resulted in a management-focused project that combines social science, physical science, and ecological impacts teams to evaluate drought vulnerability and bring decision support tools for drought preparedness (McNeeley et al. 2017a).

Even at the local level, various communities and sectors (e.g., agriculture, ranching, recreation) have begun to mitigate drought impacts through improvements of water use efficiency (Even and Ojima 2019), using healthy soil principles, destocking herd size (Kachergis et al. 2014; Yung et al 2015; Shrum et al. 2018), forage usage and storage management strategies (Yung et al. 2015, Shrum et al. 2018), and cross sectoral or business cooperation and coordination (Even and Ojima 2019). These adaptation efforts indicate that ongoing engagement among managers, extension agents, and researchers provides a useful framework for development of actionable drought-response strategies (Travis 2014; McNeeley et al. 2016; Shafer et al. 2016; McNeeley et al. 2017b; Hanberry et al. 2019).

Fires

The GP have evolved with fire and grazing over thousands of years (Pyne 1982; Wright and Bailey 1982; Twidwell et al. 2013). During the latter half of the 20th century, a reduced number of large fire events occurred due to fire-suppression measures, fragmentation of landscapes, woody encroachment, and conversion of grasslands to croplands (Twidwell et al. 2013; Donovan et al. 2017). However, the number of large fire events has been observed to increase markedly since 2000 (Steiner et al. 2015; Donovan et al. 2017; Lindley et al. 2019). There appears to be a pattern of oscillating wet and dry periods during the growing season, contributing to production of fine fuels. This period is subsequently followed by a dry period that dries these fuels, creating a highly flammable condition (Lindley et al. 2019).

Recent efforts to enhance drought monitoring (Shafer et al. 2016) and use soil moisture monitoring information that serves as a surrogate for fuel moisture conditions (Krueger et al. 2015) are being developed to assist in fire preparedness. Rangeland experts and USDA researchers have also developed an updated set of fire management strategies (Walthall et al. 2012; Steiner et al. 2015). Recommendations include building resilience among communities through improved information exchange and monitoring; enhancing coordination efforts among federal, state, and local community decision making networks with a focus on fire conditions; prudent use of prescribed fires; and enhancing research and operations collaborations to improve adaptive management practices to reduce fire risks and better manage fire events (Walthall et al. 2012; Steiner et al. 2015; Twidwell et al. 2019). In addition, further analysis of social-ecological system context of fire consequences and fire response strategies has been suggested (Twidwell et al. 2019).

Floods and extreme storm events

As described earlier regarding extreme events (i.e., storms, tornados, and flooding) in the GP, convergence of various atmospheric flows from the arctic, Pacific, and Gulf of Mexico contribute to these episodic and turbulent weather events (Kunkel et al. 2013; USGCRP 2017; Wing et al. 2018). In addition to climate change effects, a number of socioeconomic factors contribute to the increased risk to these extreme events, such as aging infrastructure, increased population, reduced social capital in rural and Native American communities (Steiner et al. 2015; McNeeley 2017; Jantarasami et al. 2018).

Strategies are being implemented to deal with flooding events. Nature-based flood plain modifications to reduce extreme flow events are being incorporated into flood avoidance plans (Williams et al. 2015; Jongman 2018). Development of combined green and gray infrastructure strategies, in addition to restoring riparian areas, is being incorporated into plans to create more resilient watersheds (Jongman 2018).

Managing for change and to enhance resilience has emerged as a necessity in dealing with climate change across the GP (West et al. 2009). An example of this is demonstrated by the rebuilding efforts following the devastating tornado that ravaged Greensburg, Kansas in May 2007. The community decided to build a more resilient community based on sustainability design principles and undertook a number of townhall meetings and coordination with federal programs to develop a long-term strategy in rebuilding this rural community (https://www.huduser.gov/portal/periodicals/em/winter15/highlight3.html). The effort has resulted in revising building codes so that many more buildings are now able to withstand 200 mph winds and are constructed according to the Leadership in Energy and Environmental Design standards. However, unintended effects to lower-income members of the community may have also been experienced, and these households were not able to wait for the reconstruction of the town or able to invest in the redesign processes and have relocated elsewhere (O'Brien et al. 2012).

Advancement of coproduction of adaptation strategies

As climate change continues to affect natural resources in the GP, enhanced engagement among researchers, managers, and land owners in the region is needed to facilitate coproduction of actionable adaptation strategies. Development of coproduced adaptive management strategies can lead to more actionable climate response strategies (Derner and Augustine 2016; Fernandez-Gimenez et al. 2019; Hanberry et al. 2019). For example, the water management practices to deal with rapid onset of droughts and water allocation among cropping, ranching, and conservation goals described earlier in the drought section was a successful collaborative effort including the Wind River Indian Reservation's Office of Tribal Water Engineer (McNeeley et al. 2017b). Driven by tribal water manager needs, this engagement process supported the development of information tools and drought condition maps to better inform resource management decision related to ranching, cropping, and wildlife management (McNeeley et al. 2016, 2017b). Additional efforts have been undertaken to enhance localized climate change information to national parks and to state wildlife adaptation planning efforts to indicate potential climate shifts impacting critical natural resources of interest (Lawrence and Runyon 2019; Schuurman et al. 2019). These efforts provide opportunities for enhanced dialogue among land managers, researchers, extension agents, and decision makers across multiple institutional structures (Derner and Augustine 2016; Averyt et al. 2018; Even and Ojima 2019; Hanberry et al. 2019; Kennedy et al. 2016).

As research related to climate change impacts is rapidly advancing, managers are often challenged by the speed of these developments to incorporate these advances into their set of management tools. Likewise, research findings are often not useable to the management community due to not fitting the information needs of the management problem. Engagement with managers and researchers is often needed to facilitate the translation of these research tools into management tools. These efforts have restructured the research agenda to codevelop research information in a more usable form that managers can more readily use (Dewes et al 2017; Peck et al 2019). Two examples of transition of research developments into useable management information codeveloped with managers and practitioners related to drought forecasts and projection of forage production are provided.

The first example is the development and application of the Evaporative Demand Drought Index (EDDI). EDDI is a real-time drought monitoring tool that incorporates daily meteorological data (Rangwala et al. 2015; Hobbins et al. 2016; Dewes et al. 2017). The tool serves as an indicator of both long-term drought and "flash" drought, which occurs on the scale of a few weeks. The tool's short-term indicators can be used by irrigators, for example, to track water needs on a day-to-day basis. Long-term indicators (e.g., 6-month forecasts) can be used for predictions such as wildfire risk (McEvoy et al. 2019). The transition from a research method to a useable forecasting tool was enabled through a set of numerous collaborations with water and natural resource managers, ranching communities, and Native American community leaders. EDDI is available on the Western Water Assessment Climate Dashboard page.[1]

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[1] wwa.colorado.edu/climate/dashboard2.html.

Another example is forage forecasts for use in adjusting stocking rates in the GP. Forage production is a key ecosystem service that supports wildlife and ranching activities across the GP. The forecasting tool, Grass-Cast (Chen et al. 2019; Hartman et al. 2020), provides growing season estimates of forage production that enables ranchers to manage herd size at appropriate levels (Peck et al. 2019).[2]

This forage forecasting tool was initially developed by Dr. W. J. Parton at Colorado State University (Chen et al. 2019; Hartman et al. 2020) and is being tested with rancher groups convened by the USDA Northern Plains Climate Hub. Grass-Cast provides projections of current growing season total grass production in rangelands across the GP. The forecasts are based on remote sensing estimates of aboveground net primary production and growing season climate outlooks provided by NOAA through a collaboration with the University of Nebraska. Forage estimates are provided initially in late April, followed by weekly updates based on a combination of observed weather conditions and seasonal climate projections for the region. The forage production values are generated using a grassland ecosystem model that has been developed at Colorado State University, DayCent (Parton et al. 1998; Chen et al. 2019).

Various federal efforts are evolving with collaborations developing with state agencies, universities, commodity groups, nongovernmental organization (NGO), and local operators (Steiner et al. 2015; Averyt et al. 2018; Fernandez-Gimenez et al. 2019). These efforts embrace collaborative engagement that more closely aligns with local needs and includes these steps:

- Develop an effective two-way interaction between resource managers and researchers for the codevelopment of usable information and adaptation strategies.
- Leverage existing resources through collaborative approaches across partner members and other entities, including tribal, federal, state, and NGO communities.
- Develop value-added efforts that provide usable information between resource managers and scientific communities.
- Provide funding mechanisms to enable resource manager led efforts to codevelop adaptation strategies with relevant partners (e.g., access to Wildlife Conservation Society's Climate Adaptation Fund; BIA or EPA grants on tribal lands; USDA or NOAA adaptation planning grants).

These engagement approaches would enable codevelopment of actionable science to address natural resource issues emerging to meet climate challenges. These efforts incorporate various levels of coproduction in support of developing appropriate adaptive management strategies for specific land use management needs. There is a general recognition that coproduction efforts have large benefits associated with close collaboration between the user and research communities in developing research that meets their needs more directly (O'Brien et al. 2012; Yung et al. 2015; Fernandez et al. 2019). However, it is also recognized that this engagement comes with an additional commitment of time, resources, and partnership, which are often outside the normal efforts of typical research efforts. So mechanisms are needed to foster and sustain these partnerships and interactions between the management and research entities.

Conclusions and Implications

Climate change continues to emerge as an issue that will challenge management operations and impact livelihoods in the GP. Changing seasonal patterns of atmospheric flows and continued warming of atmosphere will increase weather variability and extremes and impact natural resources critical to key ecosystem services for wildlife, conservation, agricultural, recreational, and livelihood needs. Collaborative efforts between researchers and management professionals are and will enhance development of useful management options to emerging climate change impacts. In addition, greater integration of social science approaches in the analysis of climate change impacts and adaptation options of rural livelihoods in the GP need to be supported.

Joint activities among various federal, state, and university units across the GP are providing opportunities for enhanced stakeholder dialogue, engagement on resource management issues, and the codesign and coproduction of research activities to support stakeholder and manager concerns more effectively. These efforts are leading to improved "climate-smart" research-management partnerships and the implementation of improved activities to reduce climate sensitivity and risk, and they increase resiliency to climate variability and change. These efforts are leading to the development of strategies to better coordinate among local, state, federal, and tribal agencies to provide a more comprehensive information exchange between researchers and managers that can be more readily used in adaptation planning, including analysis of impacts and consequences to guide development of specific strategies to cope with a changing climate.

Declaration of Competing Interest

We have no conflicts of interest. We are supported by federal grants and Colorado State University employees.

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References

Adger, W.N., Arnell, N.W., Tompkins, E.L., 2005. Successful adaptation to climate change across scales. Global Environmental Change 15, 77–86.

Adger, W.N., 2006. Vulnerability. Global Environmental Change 16, 268–281.

Algarra, I., Eiras-Barca, J., Miguez-Macho, G., Nieto, R., Gimeno, L., 2019. On the assessment of the moisture transport by the Great Plains low-level jet. Earth System Dynamics 10, 107–119.

Averyt, K., Derner, J.D., Dilling, L., Guerrero, R., Joyce, L.A., McNeeley, S., McNie, E., Morisette, J., Ojima, D.S., O'Malley, R, 2018. Regional climate response collaboratives: multi-institutional support for climate resilience. Bulletin of the American Meteorological Society 99, 891–898.

Barnett, J., Evans, L.S., Gross, C., Kiem, A.S., Kingsford, R.T., Palutikof, J.P., Pickering, C.M., Smithers, S.G., 2015. From barriers to limits to climate change adaptation: path dependency and the speed of change. Ecology and Society 20 (3), 5.

Beeton, T.A., McNeeley, S.M., Miller, B.W., Ojima, D.S., 2019. Grounding simulation models with qualitative case studies: toward a holistic framework to make climate science usable for US public land management. Climate Risk Management 23, 50–66.

Boustead, J.M., Mayes, B.E., Gargan, W., Leighton, J.L., Phillips, G., Schumacher, P.N., 2013. Discriminating environmental conditions for significant warm sector and boundary tornadoes in parts of the Great Plains. AMS Weather and Forecasting 28, 1498–1523.

Chen, M., Parton, W.J., Del Grosso, S.J., Hartman, M.D., Day, K.A., Tucker, C.J., Derner, J.D., Knapp, A.K., Smith, W.K., Ojima, D.S., Gao, W., 2017. The signature of sea surface temperature anomalies on the dynamics of semiarid grassland productivity. Ecosphere 8 (12), e02069.

Chen, M., Parton, W.J., Hartman, M.D., Del Grosso, S.J., Smith, W.K., Knapp, A.K., Lutz, S., Derner, J.D., Tucker, C.J., Ojima, D.S., Volesky, J.D., Stephenson, M.B., Schacht, W.H., Gao, W., 2019. Assessing precipitation and AET as controls of Great Plains plant production. Ecosphere 10 (10), e02889. doi:10.1002/ecs2.2889, pgs 1–17.

Chu, J.-E., Timmermann, A., Lee, J.-Y., 2019. North American April tornado occurrences linked to global sea surface temperature anomalies. Science Advances 5, eaaw9950.

Conant, R.T., Kluck, D., Anderson, M., Badger, A., Boustead, B.M., Derner, J., Farris, L., Hayes, M., Livneh, B., McNeeley, S., Peck, D., Shulski, M., Small, V., 2018. Northern Great Plains. In: Impacts, Risks, and Adaptation in the United States.

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[2] http://grasscast.agsci.colostate.edu/.

In: Reidmiller, D.R., Avery, C.W., Easterling, D.R., Kunkel, K.E., Lewis, K.L.M., Maycock, T.K., Stewart, B.C. (Eds.), Fourth National Climate Assessment, Volume II. US Global Change Research Program, Washington, DC, USA, pp. 941–986 http://nca2014.globalchange.gov/report/regions/great-plains.

Danco, J.F., Martin, E.R., 2018. Understanding the influence of ENSO on the Great Plains low-level jet in CMIP5 models. Climate Dynamics 51, 1537–1558.

Derner, J.D., Augustine, D.J, 2016. Adaptive management for drought on rangelands. Rangelands 38, 211–215.

Dewes, C.F., Rangwala, I., Barsugli, J.J., Hobbins, M.T., Kumar, S., 2017. Drought risk assessment under climate change is sensitive to methodological choices for the estimation of evaporative demand. PLoS ONE 12 (3), e0174045.

Dong, X., Xi, B., Kennedy, A., Feng, Z., Entin, J.K., Houser, P.R., Schiffer, R.A., L'Ecuyer, T., Olson, W.S., Hsu, K.L., Liu, W.T., Lin, B., Deng, Y., Jiang, T, 2011. Investigation of the 2006 drought and 2007 flood extremes at the Southern Great Plains through an integrative analysis of observations. Journal of Geophysical Research 116, D03204.

Donovan, V.M., Wonkka, C.L., Twidwell, D., 2017. Surging wildfire activity in a grassland biome. Geophysical Research Letters 44, 5986–5993.

Eiser, J.R., Bostrom, A., Burton, I., Johnston, D.M., McClure, J., Paton, D., van der Pligt, J., White, M.P., 2012. Risk interpretation and action: a conceptual framework for responses to natural hazards. International Journal of Disaster Risk Reduction 1, 5–16.

Even, T., Ojima, D.S., 2019. Changing weather and livelihoods in rural Colorado: a report on 21st century impacts and adaptation in the farming, ranching, and outdoor recreation sectors. Report prepared for the Natural Resource Ecology Laboratory. Colorado State University, Fort Collins, CO, USA Available at: https://www.nrel.colostate.edu/projects/colorado-rural-adaptation/.

Fassnacht, S.R., Cherry, M.L., Venable, N.B.H., Saavedra, F, 2016. Snow and albedo climate change impacts across the United States northern Great Plains. The Cryosphere 10, 329–339.

Feng, Z., Leung, L.R., Hagos, S., Houze, R.A., Burleyson, C.D., Balaguru, K., 2016. More frequent intense and long-lived storms dominate the springtime trend in central US rainfall. Nature Communications 7, 13429.

Fernández-Giménez, M.E., Augustine, D.J., Porensky, L.M., Wilmer, H., Derner, J.D., Briske, D.D., Stewart, M.O., 2019. Complexity fosters learning in collaborative adaptive management. Ecology and Society 24, 29.

Gerken, T., Bromley, G.T., Ruddell, B.L., Williams, S., Stoy, P.C., 2018. Convective suppression before and during the United States Northern Great Plains flash drought of 2017. Hydrology Earth Systems Science 22, 4155–4163.

Griffin, E.R., Friedman, J.M., 2017. Decreased runoff response to precipitation, Little Missouri River Basin, Northern Great Plains, USA. Journal of the American Water Resources Association (JAWRA) 53, 576–592.

Gross, J. E., M. Tercek, K. Guay, M. Talbert, T. Chang, A. Rodman, D. Thoma, P. Jantz, and J. T. Morisette. 2016. Analyses of historical and projected climates to support climate adaptation in the northern Rocky Mountains. Climate Change in Wildlands: Pioneering Approaches to Science and Management. In: Hansen, A. J., W. B. Monahan, S. T. Olliff, and D. M. Theobald, Eds., Island Press/Center for Resource Economics, Washington, DC, 55–77. 10.5822/978-1-61091-713-1_4.

Hanberry, B., Reeves, M.C., Brischke, A., Hannemann, M., Hudson, T., Mayberry, R., Ojima, D.S., Prendeville, H.R., Rangwala, I., 2019. Managing effects of drought in the Great Plains. In: Vose, J.M., Peterson, D.L., Luce, C.H., Patel-Weynand, T. (Eds.), Chapter 7. Effects of drought on forests and rangelands in the United States: Translating science into management responses. Gen. Tech. Rep. WO-98. US Department of Agriculture, Forest Service, Washington, DC. USA, pp. 141–164.

Hartman, M.D., Parton, W.J., Derner, J.D., Schulte, D.K., Smith, W.K., Peck, D.E., Day, K.A., Del Grosso, S.J., Lutz, S., Fuchs, B.A., Chen, M., Gao, W., 2020. Seasonal grassland productivity forecast for the U.S. Great Plains using Grass-Cast. Ecosphere 11, e03280.

Hibbard, K.A., Meehl, G.H., Cox, P., Friedlingstein, P., 2007. A strategy for climate change stabilisation experiments. EOS 88, 217–221.

Higgins, R.W., Yao, Y., Yarosh, E.S., Janowiak, J.E., Mo, K.C., 1997. Influence of the Great Plains low-level jet on summertime precipitation and moisture transport over the central United States. Journal of Climate 10, 481–507.

Hobbins, M., Wood, A., McEvoy, D., Huntington, J., Anderson, M., Hain, C., et al., 2016. The evaporative demand drought index. Part I: Linking drought evolution to variations in evaporative demand. Journal of Hydrometeorology 17, 1745–1761.

Hoell, A., Perlwitz, J., Dewes, C., Wolter, K., Rangwala, I., Quan, X.-W., Eischcheid, J., 2018. Anthropogenic contributions to the intensity of the 2017 United States Northern Great Plains drought. Bulletin of the American Meteorological Society doi:10.1175/BAMS-D-18-0127.1.

IPCC, 2013. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA 1535 p.

Jantarasami, L.C., Novak, R., Delgado, R., Marino, E., McNeeley, S., Narducci, C., Raymond-Yakoubian, J., Singletary, L., Powys Whyte, K.Reidmiller, D.R., Avery, C.W., Easterling, D.R., Kunkel, K.E., Lewis, K.L.M., Maycock, T.K., Stewart, B.C. (Eds.), 2018. Tribes and indigenous peoples. Impacts, risks, and adaptation in the United States: fourth national climate assessment, volume II 572–603.

Jongman, B., 2018. Effective adaptation to rising flood risk. Natural Communitires 9, 1986.

Kachergis, E., Derner, J.D., Cutts, B.B., Roche, L.M., Eviner, V.T., Lubell, M.N., Tate, K.W., 2014. Increasing flexibility in rangeland management during drought. Ecosphere 5, art77.

Kennedy, S.M., Burbach, M.E., Sliwinski, M.S., 2016. Sustainable grassland management: an exploratory study of progressive ranchers in Nebraska. Sustainable Agriculture Research 5, 103–113.

Kloesel, K., Bartush, B., Banner, J., Brown, D., Lemory, J., Lin, X., McManus, G., Mullens, E., Nielsen-Gammon, J., Shafer, M., Sorenson, C., Sperry, S., Wildcat, D., Ziolkowska, J, 2018. Southern Great Plains. In: Reidmiller, D.R., Avery, C.W., Easterling, D.R., Kunkel, K.E., Lewis, K.L.M., Maycock, T.K., Stewart, B.C. (Eds.), Impacts, risks, and adaptation in the United States: Fourth National Climate Assessment, Volume II. US Global Change Research Program, Washington, DC, USA, pp. 987–1035.

Knight, D.B., Davis, R.E., 2009. Contribution of tropical cyclones to extreme rainfall events in the southeastern United States. Journal of Geophysical Research 114, D23102.

Kolstad, E.W., Breiteig, T., Scaife, A.A., 2010. The association between stratospheric weak polar vortex events and cold air outbreaks in the northern hemisphere. Quarterly Journal of Royal Meteorology Society 136, 886–893.

Kretschmer, M., Coumou, D., Agel, L., Barlow, M., Tziperman, E., Cohen, J., 2018. More-persistent weak stratospheric polar vortex states linked to cold extremes. Bulletin of the American Meteorological Society 99 (1), 49–60. doi:10.1175/BAMS-D-16-0259.1.

Krueger, E.S., Ochsner, T.E., Engle, D.M., Carlson, J.D., Twidwell, D., Fuhlendorf, S.D., 2015. Soil moisture affects growing-season wildfire size in the southern Great Plains. Soil Science Society of America Journal 79, 1567–1576.

Kunkel, K.E, Stevens, L.E., Stevens, S.E., Sun, L., Janssen, E., Wuebbles, D., Kruk, M.C., Thomas, D.P., Shulski, M., Umphlett, N., Hubbard, K., Robbins, K., Romolo, L., Akyuz, A., Pathak, T., Bergantino, T., Dobson, J.G., 2013. Regional climate trends and scenarios for the US national climate assessment. Part 4. Climate of the US Great Plains. NOAA Technical Report NESDIS, Washington, DC, USA 142-144. 82 p.

Lavers, D.A., Villarini, G., 2013. Atmospheric rivers and flooding over the central United States doi:10.1175/JCLI-D-13-00212.1.

Lawrence, D.J., Runyon, A.N., 2019. Implications of climate change for the water supply of the Chisos Mountains developed area: Big Bend National Park technical assistance request 4945. Natural Resource Report. NPS/NRSS/CCRP/NRR2019/2045. National Park Service. Fort Collins, Colorado.

Lindley, T.T., Speheger, D.A., Day, M.A., Murdoch, G.P., Smith, B.R., Nauslar, N.J., Daily, D.C., 2019. Megafires on the southern Great Plains. Journal of Operational Meteorology 7, 164–179.

Mader, T.L., 2003. Environmental stress in confined beef cattle. Journal of Animal Science 81, E110–E119.

Marshall, N.A., Stokes, C.J., Webb, N.P., Marshall, P.A., Lankester, A.J., 2014. Social vulnerability to climate change in primary producers: a typology approach. Agriculture, Ecosystems and Environment 186, 86–93.

Martin, J.T., Pederson, G.T., Woodhouse, C.A., Cook, E.R., McCabe, G.J., Anchukaitis, K.J., Wise, E.K., Erger, P.J., Dolan, L., McGuire, M., Gangopadhyay, S., 2020. Increased drought severity tracks warming in the United States' largest river basin. Proceedings of the National Academy of Sciences 117, 11328–11336.

McEvoy, D.J., Hobbins, M., Brown, T.J., VanderMolen, K., Wall, T., Huntington, J.L., Svoboda, M., 2019. Establishing relationships between drought indices and wildfire danger outputs: a test case for the California–Nevada drought early warning system. Climate 7, 52.

McGeehin, M.A., Mirabelli, M., 2001. The potential impacts of climate variability and change on temperature-related morbidity and mortality in the United States. Environmental Health Perspectives 109, 185.

McNeeley, S.M., Beeton, T.A., Ojima, D.S., 2016. Drought risk and adaptation in the interior United States: understanding the importance of local context for resource management in times of drought. *Weather, Climate, and Society* 8, 147–161.

McNeeley, S.M., 2017. Sustainable climate change adaptation in Indian country. Weather, Climate and Society 9, 393–404.

McNeeley, S.M., Even, T.L., Gioia, J.B.M., Knapp, C.N., Beeton, T.A, 2017a. Expanding vulnerability assessment for public lands: the social complement to ecological approaches. Climate Risk Management 16, 106–119.

McNeeley, S.M., Dewes, C.F., Stiles, C.J., Beeton, T.A., Rangwala, I., Hobbins, M.T., Knutson, C.L., 2017b. Anatomy of an interrupted irrigation season: micro-drought at the Wind River Indian Reservation. *Climate Risk Management* doi:10.1016/j.crm.2017.09.004.

Moss, R.H., Babiker, M., Brinkman, S., Calvo, E., Carter, T., Edmonds, J., Elgizouli, I., Emori, S., Erda, L., Hibbard, K., Jones, R., Kainuma, M., Kelleher, J., Lamarque, J.F., Manning, M., Matthews, B., Meehl, J., Meyer, L., Mitchell, J., Nakicenovic, N., O'Neill, B., Pichs, R., Riahi, K., Rose, S., Runci, P., Stouffer, R., van Vuuren, D., Weyant, J., Wilbanks, T., van Ypersele, J.-P, … Zurek, M., 2008. Towards new scenarios for analysis of emissions, climate change, impacts, and response strategies. Intergovernmental Panel on Climate Change, Geneva 132 p. Available at http://www.ipcc.ch/pdf/supporting-material/expert-meeting-report-scenarios.pdf.

National Weather Service. 2013. Available at: https://www.weather.gov/unr/2013-10-03_05. Accessed march 30, 2021.

NOAA (National Oceanic and Atmospheric Administration). 2012. State of the climate: drought Annual 2011. Accessed August 1, 2020.

NOAA. 2013. NOAA Technical Report NESDIS 142-4. Regional climate trends and scenarios for the US national climate assessment. Part 4. Climate of the US Great Plains.

O'Brien, K., Pelling, M., Patwardhan, A., Hallegatte, S., Maskrey, A., Oki, T., Oswald-Spring, U., Wilbanks, T., Yanda, P.Z, 2012. Toward a sustainable and resilient future. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M., Midgley, P.M. (Eds.), Managing the risks of extreme events and disasters to advance climate change adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 437–486.

Ojima, D.S., Steiner, J., McNeeley, S., Cozetto, K., Childress, A.N., 2015. Great Plains Regional Technical Input Report. Island Press, Washington, DC, USA 224 Pages.

Otkin, J.A., Svoboda, M., Hunt, E.D., Ford, T.W., Anderson, M.C., Hain, C., Basara, J.B., 2018. Flash droughts: a review and assessment of the challenges imposed by rapid onset droughts in the United States. Bulletin of the American Meteorological Society 99, 911–919.

Parton, W.J., Hartman, M.D., Ojima, D.S., Schimel, D.S., 1998. DAYCENT: its land surface submodel: description and testing. Global Planetary Changes 19, 35–48.

Peck, D., Derner, J., Parton, W.J., Hartman, M., Fuchs, B., 2019. Flexible stocking with Grass-Cast: A new grassland productivity forecast to translate climate outlooks for ranchers. Western Economics Forum 17, 24–39.

Peterson, T.C., Heim, R.R., Hirsch, R., Kaiser, D.P., Brooks, H., Diffenbaugh, N.S., Wuebbles, D., 2013. Monitoring and understanding changes in heat waves, cold waves, floods, and droughts in the United States: State of knowledge. Bulletin of The American Meteorological Society 94, 821–834.

Pyne, S.J., 1982. Fire in America. University of Washington Press, Seattle, WA, USA [1997 edition available at uwapress.uw.edu/book/9780295975924/fire-in-america/].

Rangwala, I., Hobbins, M., Barsugli, J., Dewes, C., 2015. EDDI: A powerful tool for early drought warning. Western Water Assessment, Boulder, CO, USA 2 p.

Rippey, B.R., 2015. The US drought of 2012. Weather and climate extremes 10, 57–64.

Rosenberg, N.J., 1987. Climate of the Great Plains region of the United States. Great Plains Quarterly 7, 22–32.

Schumacher, R.S., Johnson, R.H, 2006. Characteristics of US extreme rain events during 1999–2003. Weather Forecasting 21, 69–85.

Schuurman, G.W., Symstad, A., Miller, B.W., Runyon, A.N., Ohms, R., 2019. Climate change scenario planning for resource stewardship: applying a novel approach in Devils Tower National Monument NPS/NRSS/CCRP/NRR2019/2052. National Park Service. Fort Collins, Colorado.

Shafer, M., Ojima, D.S., Antle, J.M., Kluck, D., McPherson, R.A., Petersen, S., Scanlon, B., Sherman, K., 2014. Ch. 19: Great Plains. Climate change impacts in the United States: The Third National Climate Assessment. In: Melillo, J.M., Richmond, T.C., Yohe, G.W. (Eds.), US Global Change Research Program, pp. 441–461. Published on the web: http://nca2014.globalchange.gov/report/regions/great-plains.

Shafer, M., Brown, D., McNutt, C, 2016. Managing the 2011 drought: a climate services partnership. In: Parris, A., Garfin, G., Dow, K., Meyer, R., Close, S.L. (Eds.), Climate in context: Science and society partnering for adaptation. Wiley & Sons, West Sussex, UK.

Shrum, T.R., Travis, W.R., Williams, T.M., Lih, E., 2018. Managing climate risks on the ranch with limited drought information. Climate Risk Management 20, 11–26.

Squitieri, B.J., Gallus Jr., W.A., 2016. WRF forecasts of Great Plains nocturnal low-level jet-driven MCSs. Part II: Differences between strongly and weakly forced low-level jet environments. AMS Weather and Forecasting 31, 1491–1510.

Steiner, J.L., J.M. Schneider, C. Pope, S. Pope, P. Ford, R.F. Steele. 2015. Southern Plains Assessment of Vulnerability and Preliminary Adaptation and Mitigation Strategies for Farmers, Ranchers, and Forest Land Owners, T. Anderson, Ed., United States Department of Agriculture, 61 pp.

Travis, W.R., 2014. Weather and climate extremes: Pacemakers of adaptation? Weather and Climate Extremes 5–6, 29–39.

Twidwell, D., Rogers, W.E., Fuhlendorf, S.D., Wonkka, C.L., Engle, D.M., Weir, J.R., Kreuter, U.P., Taylor Jr., C.A., 2013. The rising Great Plains fire campaign: citizens' response to woody plant encroachment. Frontiers in Ecology and the Environment 11, e64–e71.

Twidwell, D., Wonkka, C.L., Wang, H.-H., Grant, W.E., Allen, C.R., Fuhlendorf, S.D., Garmestanie, A.S., Angelerf, D.G., Taylor Jr., C.A., Kreuterh, U.P., Rogers, W.E, 2019. Coerced resilience in fire management. Journal of Environmental Management 240, 368–373.

US Census Bureau. 2000. 2000 Census data. api.census.gov/data/2000/dec/sf1?. Accessed August 1 2020.

US Census Bureau. 2010. 2010 Census data: Population size. US Bureau of the Census. Available at: http://2010.census.gov/2010census/data/.

USDA. 2012. Atlas of rural and small-town America, US Department of Agriculture, Economic Research Service. Available at: http://www.ers.usda.gov/data-products/atlas-of-rural-and-small-town-america/go-to-the-atlas.aspx.]

USGCRP, 2017. In: Wuebbles, D.J., Fahey, D.W., Hibbard, K.A., Dokken, D.J., Stewart, B.C., Maycock, T.K. (Eds.), Climate science special report: fourth national climate assessment, Volume I. US Global Change Research Program, Washington, DC, USA 470 p.

van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, F-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K., 2011. The representative concentration pathways: An overview. Climatic Change 109, 5.

Walthall, C.L., Hatfield, J., Backlund, P., Lengnick, L., Marshall, E., Walsh, M., Adkins, S., Aillery, M., Ainsworth, E.A., Ammann, C., Anderson, C.J., Bartomeus, I., Baumgard, L.H., Booker, F., Bradley, B., Blumenthal, D.M., Bunce, J., Burkey, K., Dabney, S.M., Delgado, J.A., Dukes, J., Funk, A., Garrett, K., Glenn, M., Grantz, D.A., Goodrich, D., Hu, S., Izaurralde, R.C., Jones, R.A.C., Kim, S-H., Leaky, A.D.B., Lewers, K., Mader, T.L., McClung, A., Morgan, J., Muth, D.J., Nearing, M., Oosterhuis, D.M., Ort, D., Parmesan, C., Pettigrew, W.T., Polley, W., Rader, R., Rice, C., Rivington, M., Rosskopf, E., Salas, W.A., Sollenberger, L.E., Srygley, R., Stöckle, C., Takle, E.S., Timlin, D., White, J.W., Winfree, R., Wright-Morton, L., Ziska, L.H, 2012. Climate change and agriculture in the United States: effects and adaptation. USDA Technical Bulletin 1935, Washington, DC . 186 p.

Wang, T., Hamann, A., Spittlehouse, D., Carroll, C, 2016. Locally downscaled and spatially customizable climate data for historical and future periods for North America. PLoS One 11 (6), e0156720.

West, J.M., Julius, S.H., Kareiva, P., Enquist, C., Lawler, J.L., Petersen, B., Johnson, A.E., Shaw, M.R., 2009. US natural resources and climate change: Concepts and approaches for management adaptation. Environmental Management 44, 1001–1021.

Williams, J.E., Neville, H.M., Haak, A.L., Colyer, W.T., Wenger, S.J., Bradshaw, S., 2015. Climate change adaptation and restoration of western trout streams: Opportunities and strategies. Fisheries 40 (7), 304–317.

Wing, O., Bates, P., Smith, A., Sampson, C., Johnson, K., Fargione, J., Morefield, P., 2018. Estimates of present and future flood risk in the conterminous United States. Environmental Research Letters 13, 034023.

Woodhouse, C.A., Lukas, J.J., Brown, P.M., 2002. Drought in the western Great Plains, 1845–56: Impacts and implications. Bulletin of the American Meteorological Society 83, 1485–1494.

Woodhouse, C.A., Meko, D.M., MacDonald, G.M., Stahle, D.W., Cook, E.R., 2010. A 1,200-year perspective of 21st century drought in southwestern North America. PNAS 107, 21283–21288.

Wright, H.A., Bailey, A.W. 1982: Fire Ecology—United States and southern Canada. Hoboken, NJ: John Wiley and Sons. 528 p. Available at: www.wiley.com/en-us/Fire+Ecology%3A+United+States+and+Southern+Canada-p-9780471090335.

Yung, L., Phear, N., DuPont, A., Montag, J., Murphy, D., 2015. Drought adaptation and climate change beliefs among working ranchers in Montana. Weather, Climate, and Society 7, 281–293.