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# Vulnerability of rangeland beef cattle production to climate-induced NPP fluctuations in the US Great Plains

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## Abstract

The vulnerability of rangeland beef cattle production to increasing climate variability in the US Great Plains has received minimal attention in spite of potentially adverse socioeconomic and ecological consequences. Vulnerability was assessed as the frequency and magnitude of years in which net primary production (NPP) deviated >±25% from mean values, to represent major forage surplus and deficit years, for a historic reference period (1981–2010), mid-century (2041–2065), and late-century (2075–2099) periods. NPP was simulated by MC2, a dynamic global vegetation model, driven by five climate projections for representative concentration pathway (RCP) 4.5 and 8.5. Historically, 4–4.7 years per decade showed either NPP surpluses or deficits. The future number of extreme years increased to 5.4–6.4 and 5.9–6.9 per decade for RCP 4.5 and 8.5, respectively, which represents an increase of 33%–56% and 38%–73%, respectively. Future simulations exhibited increases in surplus years to between 3 and 5 years in the Northern Plains and 3–3.5 in the Southern Plains. The number of deficit years remained near historic values of 2 in the Northern Plains, but increased in the Southern Plains from 2.5 to 3.3 per decade. Historically, NPP in extreme surplus and deficit years both deviated 40% from mean NPP in all three regions. The magnitude of deficit years increased by 6%–17% in future simulations for all three regions, while the magnitude of surplus years decreased 16% in the Northern Plains and increased 16% in the Southern Plains. The Southern Plains was the only region to exhibit an increase in the magnitude of both surplus and deficit years. Unprecedented future variability of NPP may surpass the existing adaptive capacity of beef producers and adversely impact the economic viability of rangeland cattle production and ecological sustainability of rangeland resources.

**KEYWORDS**
adaptive capacity, climate change, ecological sustainability, economic sustainability, exposure, sensitivity

## 1 | INTRODUCTION

Interannual precipitation variability on grazing lands is 25% greater than for the average global land area, and it is projected to further increase by 10% over approximately one-half of the world's grazing lands (Sloat et al., 2018). Increasing precipitation variability is anticipated to adversely affect the provision of ecosystem services from these lands, including livestock production (Godde et al., 2019). Climate variability may have contributed to a northward shift in the relative proportion of brood cows in the US Great Plains over the past several decades (Klemm & Briske, 2019). This distributional shift was especially evident in the 2011–2014 drought, where the greatest relative decreases in cow numbers occurred in the Southern and Central Plains, which had the highest mean annual temperatures (MAT) and the largest decrease in mean annual precipitation (MAP) in 2012 compared to the 1975–2017 average (Klemm & Briske, 2019). This suggests that the 20th century may not represent an effective climate analog for future variability in the Great Plains (Clark et al., 2002; Nippert, Knapp, & Briggs, 2006).

Increasing climate variability has important consequences for agriculture as evidenced by the severe drought across the Great Plains from 2011 to 2014 that resulted in major production and economic losses for both cropping and livestock systems (Rippey, 2015). In the case of rangeland beef cattle production, drought reduces both forage quantity and quality, which increases operating costs and reduces profits as a result of supplemental feeding, low animal production, and costly destocking–restocking cycles (Bastian et al., 2006; Kachergis et al., 2014; Torell, Murugan, & Ramirez, 2010). Drought years have disproportionately negative impacts because increases in forage production and calf gains in wet years are insufficient to overcome the adverse consequences of dry years (Hamilton, Ritten, Bastian, Derner, & Tanaka, 2016). Alternatively, years with high precipitation may challenge the ability of producers to convert abundant forage into animal production, and increase the risk of flooding, soil erosion, and subsequent wildfires.

Collectively, these considerations indicate that rangeland beef cattle production is vulnerable to increasing climate variability (Irisarri, Derner, Ritten, & Peck, 2019; Ritten, Frasier, Bastian, & Gray, 2010). Yet, this vulnerability has received minimal attention considering the potential socioeconomic consequences to the region (Shrum, Travis, Williams, & Lih, 2018). The Great Plains supports approximately 50% of the total US beef cow herd and generated livestock revenues of $58 B in 2017 (USDA ERS, 2019; USDA NASS, 2018). However, neither the potential economic losses to increasing climate variability nor benefits of adaptation strategies are as well defined as they are in cropping systems, presumably because of the greater complexity and the longer duration of the cattle production cycle (Klemm & Briske, 2019).

Vulnerability describes the degree to which a system is likely to experience harm in response to exposure to a stressor or hazard, and it consists of three interrelated components—exposure, sensitivity, and adaptive capacity (Adger, 2006; Smit & Wandel, 2006). In the context of climate variability and change, exposure refers to the direct effects of warming, modified precipitation patterns, and a greater frequency and intensity of extreme weather events (Glick, Stein, & Edelson, 2011). Sensitivity describes the economic and ecological impact that exposure to stressors has on systems. In the case of beef cattle production, sensitivity represents increasing variability of forage quantity and quality, and associated impacts on animal production and economic viability. Adaptive capacity represents the ability of producers to anticipate and respond to potential or actual exposure to various stressors (Adger, 2006; Nelson et al., 2010). The capacity to effectively manage variable forage production with animal demand will reduce enterprise sensitivity by maintaining favorable cost–benefit ratios and sustainable rangeland resources.

Here, the vulnerability of beef cattle production in the US Great Plains was based on projected MAP, and MAT, and simulated total net primary production (NPP) throughout the 21st century. Vulnerability was assessed as: (a) exposure—the interannual variability of MAP and MAT throughout this century; (b) sensitivity—the frequency of years with extreme forage deficits and surpluses and the magnitude of these fluctuations compared to mean NPP; and (c) adaptive capacity—based on the assumption that the frequency and magnitude of years with forage surpluses or deficits that exceeded mean NPP by ±25% will challenge the capacity of most beef producers. Simulations were produced by a dynamic global vegetation model, MC2, that was driven by climate projections from five global change models that had been shown to effectively project historical climatic variables for the region (Bachelet, Ferschweiler, Sheehan, Sleeter, & Zhu, 2015; Klemm, Briske, & Reeves, 2020). Model simulations have previously been used to assess the future vulnerability of beef cattle production in the Great Plains and western rangelands of the United States (Reeves, Bagne, & Tanaka, 2017). An increase in the vulnerability of rangeland beef cattle production in future climates may have far reaching consequences, including land ownership, land use and cover, and the provision of diverse ecosystem services throughout the region, in addition to the nation's beef supply.

## 2 | MATERIALS AND METHODS

### 2.1 | Site description

The US Great Plains encompasses approximately 1.3 M km$^2$ in portions of 10 states in the central United States. The study domain was bound by the 95th and 105th longitude west and the 30th and 49th latitude north and it was subdivided into a Southern (30°–36°N), Central (36°–42°N), and Northern (42°–49°N) Plains region. Each region was further divided into an east and west portion along the 100th longitude west. The climate ranges from cold semiarid in the northwest to humid subtropical in the southeast and can be broadly defined as continental (Köppen, 1936). The native vegetation is primarily grassland, which is broadly categorized along an east–west precipitation gradient as tallgrass prairie, mixed grass prairie, and shortgrass prairie (Küchler, 1964). A large portion of these grasslands have been converted to cropland, primarily east of the 100th longitude (Yu & Lu, 2018). Grasslands and croplands, in approximately equal proportions, comprise 89% of the total land cover (Drummond et al., 2012).

### 2.2 | MC2 and climate models

Gridded simulations of annual, total NPP were generated by the dynamic global vegetation model MC2 (Bachelet, Ferschweiler, Sheehan, Sleeter, & Zhu, 2018) in 1/24 degree spatial resolution (ca. 4 km) and were obtained from the Conservation Biology Institute, Corvallis, OR (www.consbio.org). MC2 and its predecessor, MC1 (Bachelet, 2015; Bachelet et al., 2001), have been used extensively to investigate ecosystem responses to climate change (Bachelet et al., 2015; Daly et al., 2000; Neilson et al., 2005). The model contains three modules that simulate biogeography, biogeochemistry, and wildfire interactions (see Bachelet et al., 2015; Sheehan, Let, & Ferschweiler, 2015 for further detail). The biogeochemistry module is a modified version of the CENTURY model (Parton, Ojima, Cole, & Schimel, 1994) that simulates carbon and nitrogen cycles, including NPP and ecosystem carbon balance, decomposition, and soil respiration. NPP is determined by temperature, soil water availability, soil nitrogen, and atmospheric $CO_2$ (Bachelet et al., 2015). Projected increases in annual atmospheric $CO_2$ concentrations were prescribed by a moderate and a high radiative forcing scenario (representative concentration pathway [RCP] 4.5 and 8.5; Hayhoe et al., 2017; Riahi et al., 2011; Thomson et al., 2011).

Previous work with these model simulations has indicated that those including the fire module provide the best results for both vegetation composition and NPP in the region (Klemm et al., 2020), which corresponds to the increase in fire frequency and magnitude throughout the Great Plains (Donovan, Wonkka, & Twidwell, 2017). NPP simulations were generated with an activated fire module that simulates fire occurrence, area burned, and fire impacts including mortality, consumption of aboveground biomass, and nitrogen volatilization, to reflect a realistic occurrence of fire under assumed ignitions. Fire occurrence is simulated as discrete events in response to calculated ignition probabilities. The module operates on daily time steps by using a randomly distributed set of daily precipitation values derived from monthly precipitation values. To reflect a realistic geographic extent of a fire under assumed ignitions, the fire module limits the area burned with an algorithm based on fire return interval and years since the last fire (Bachelet et al., 2015; Sheehan et al., 2015).

Net primary production simulations of the MC2 model for 1981–2010 were driven by gridded PRISM climate observations to serve as a historic 30 year reference, a commonly used time period in climate analysis (WMO, 2011). Five future NPP simulations for mid-century (2041–2065) and late-century (2075–2099) were driven by five gridded climate projections derived from five climate models selected from the Coupled Model Intercomparison Project phase 5 (CMIP5; Taylor, Stouffer, & Meehl, 2012). Historic PRISM data were gridded to 1/24 degree (ca. 4 km) spatial resolution from station data by PRISM Climate Group, future climate data were downscaled by Abatzoglou (2013) to 1/24 degree spatial resolution using the gridMET (previously MACAv2-METDATA) method. Climate variables used were monthly minimum and maximum temperature, which were averaged and summed to MAT, and total monthly precipitation, which was summed to MAP. Future MAT and MAP were aggregated into an unweighted ensemble average of the five climate models to describe future climate trends.

The five climate models were selected from 41 available CMIP5 models, based on availability of downscaled projections (19 of 41 models) and a literature assessment of the accuracy of retrospective model projections to observed climate means and extremes prior to downscaling the projections. Projections with a seasonal precipitation bias >25% or seasonal temperature bias >4°C were excluded, and seven remaining models were ranked based on their accuracy for a number of mean and extreme variables, including winter and summer total precipitation and mean temperature, number of high precipitation days, and the number of hot days for central North America (Sheffield et al., 2013); 95th percentile of precipitation, growing season length, and daily average minimum and maximum temperatures globally (Sillmann, Kharin, Zhang, Zwiers, & Bronaugh, 2013); and model responses to changes in El Nino Southern Oscillation and multi-year trends of temperature and precipitation in the south-central United States (D. Rosendahl, personal communication). The five highest ranked models—CCSM4, GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, and MRI-CGCM3—were selected to represent a spectrum of possible future climates and consequently a range of NPP simulations.

## 2.3 | Data analysis

Data analysis focused on the variability of MAT and MAP and the frequency and magnitude of years with extreme NPP (>±25% mean) simulated by the MC2 model. The ±25% threshold for NPP variation is a general assumption focused on the adaptive capacity of beef producers, rather than a meteorologically derived value. Interannual MAT and MAP variability, defined as the absolute difference between two successive years, was calculated for each grid cell for historic values and each of the five future projections, before averaging projections for each of the three regions, three time periods, and two RCPs. Therefore, the variability of MAT and MAP is based on individual climate projections, and not the ensemble average of these projections.

Extreme NPP years were classified as years with annual NPP that were at least 25% above (surplus) or below (deficit) the mean annual NPP for the historic (1981–2010), mid-century (2041–2065), or late-century (2075–2099) periods in each of the five simulations. The frequency of extreme surplus and deficit years represents the mean number of years per decade that were at least 25% above or below mean NPP, while the magnitude describes the mean deviation of these years from mean NPP. In addition, the relative difference between mean NPP of extreme surplus and deficit years was calculated by subtracting mean NPP of extreme deficit years from mean NPP of extreme surplus years, and dividing this difference by mean NPP of all years within the respective time period (historic, mid-century, or late-century). This ratio is comparable to a coefficient of variation where 100% indicates that the mean difference in NPP between extreme surplus and deficit years is equal to mean NPP of all years for the respective period. The use of relative values eliminated the need to partition total NPP (g C/$m^2$) into above- and belowground NPP, which was not simulated separately by MC2. All values were initially calculated for each of the five simulations by grid cell, then averaged per region and time period to obtain means for each simulation, and eventually averaged across all simulations to obtain ensemble averages for each time period and RCP. The mean number of total extreme years per decade was based on the sum of mean surplus and deficit years for each region. Data analysis was conducted using the NCAR Command Language (UCAR/NCAR/CISL/TDD, 2019) and Microsoft Excel.

The MC2 model simulates total NPP (g C/m$^2$) for several herbaceous and woody life-forms (Bachelet & Turner, 2015). The contribution of various life-forms to total NPP was not presented, but previous simulations indicated that grassland remained dominant west of the 97th longitude throughout the century, with the exception of woody plant encroachment in the eastern half of the Northern Plains near the end of the century (Klemm et al., 2020). Inclusion of the woody life-form did not appear to have a disproportionate effect on total NPP because future NPP simulations east and west of the 100th longitude resulted in negligible differences between the two regions. Emphasis on interannual variability of NPP, rather than total NPP, further minimizes the consequences of using total NPP.

## 3 | RESULTS

### 3.1 | Climate projections

The ensemble average for MAT increased proportionately throughout the century in all three regions for both RCPs (Figure 1). MAT for the historic period (1981–2010) was highest in the Southern (16.9°C) and lowest in the Northern Plains (6.7°C), as was MAP (683 and 511 mm/year, respectively, Figure 1). MAT increased by 2.2 and 2.8°C for RCP 4.5 and 2.9 and 5.0°C for RCP 8.5, respectively, in mid- and late-century (Figure 1a,e). The ensemble average for MAP remained similar to historic values for all three regions, with only small increases occurring in late-century for the Northern and Central Plains for RCP 8.5 (Figure 1b–d,f–h).

Historic variability for MAT was highest in the Northern Plains, and future simulations remained relatively similar for both RCPs and time periods (Table 1). However, variability for MAT increased in the Central and Southern Plains to values comparable to those of the Northern Plains in future simulations. Historic variability for MAP was lowest in the Northern Plains and highest in the Southern Plains. These relative differences in MAP among regions remained similar throughout the 21st century for both RCPs; however, the Central Plains showed the greatest absolute increases from the historic period for both RCPs.

### 3.2 | NPP simulations

Total simulated annual NPP in the historic period was lowest in the Northern Plains and highest in the Southern Plains (Figure S1).

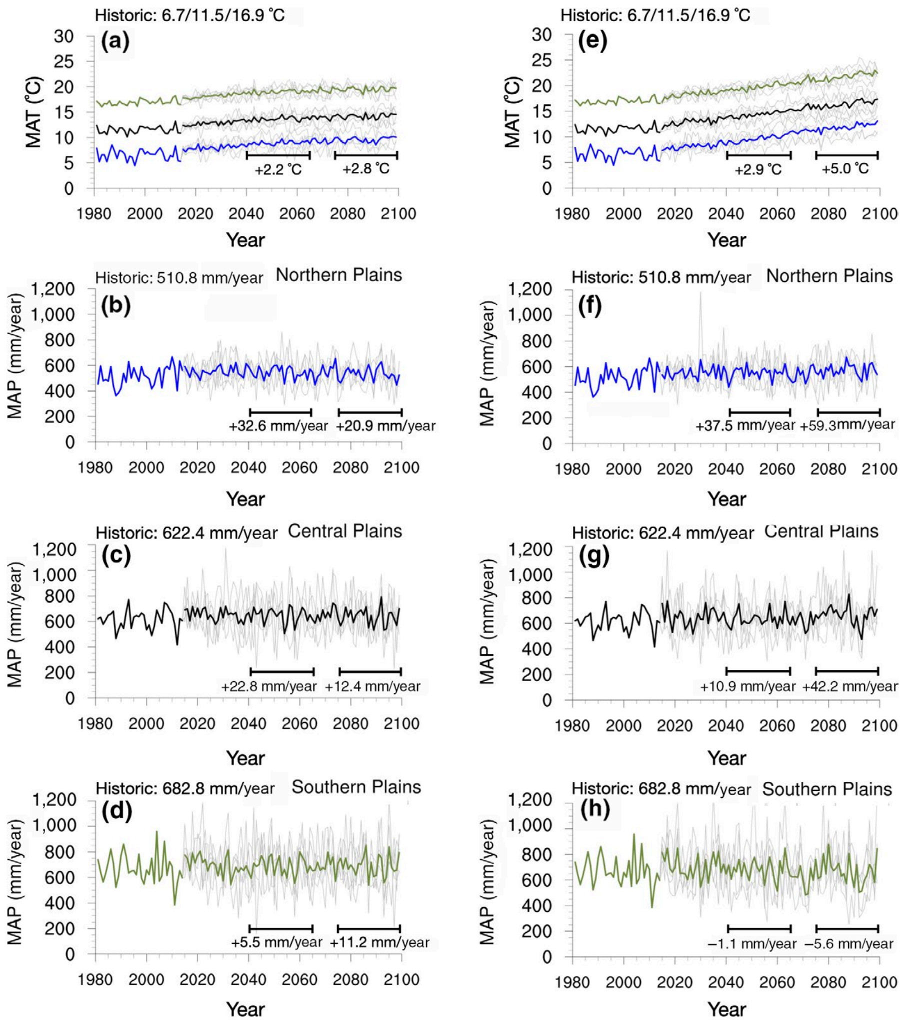


**FIGURE 1** Mean annual precipitation (MAP, b–d, f–h) and temperature (MAT, a, e) projections based on observations (1981–2014) and model projections (2015–2099) for the Northern (blue), Central (black), and Southern (green) Plains for RCP 4.5 (a–d) and 8.5 (e–h). Blue, black, and green lines represent historic observations and future ensemble averages, respectively, and gray lines (2015–2099) represent individual future model projections. Mean annual precipitation (b–d, f–h) and temperature (a, e) values are presented in the upper left of each panel, for 1981–2010 (observations) and for 2015–2099 (projections). Values in the lower right of each panel represent changes in MAP and MAT in mid- and late-century from the historic reference. RCP, representative concentration pathway [Colour figure can be viewed at wileyonlinelibrary.com]

**TABLE 1** Mean variation in MAT (a) and MAP for (b) the historic period (1981–2010), mid-century (2041–2065), and late-century (2075–2099) in the Northern (NP), Central (CP), and Southern (SP) Plains. Historic projections are based on PRISM observations, and future projections represent unweighted ensemble averages from five climate projections for RCP 4.5 and 8.5

| | Temperature (°C) | RCP 4.5 | | RCP 8.5 | |
|---|---|---|---|---|---|
| (a) | Historic | Mid-century | Late-century | Mid-century | Late-century |
| NP | 1.03 | 1.05 | 1.04 | 0.98 | 0.98 |
| CP | 0.66 | 1.06 | 0.93 | 0.88 | 0.95 |
| SP | 0.53 | 0.97 | 0.87 | 0.81 | 0.91 |
| | Precipitation (mm/year) | RCP 4.5 | | RCP 8.5 | |
| (b) | Historic | Mid-century | Late-century | Mid-century | Late-century |
| NP | 112.6 | 133.4 | 135.4 | 146.2 | 145.6 |
| CP | 129.5 | 191.8 | 198.2 | 174.2 | 197.9 |
| SP | 181.0 | 233.4 | 237.8 | 216.1 | 227.5 |

Abbreviations: MAP, mean annual precipitation; MAT, mean annual temperature; RCP, representative concentration pathway.

Future mean NPP increased in all three regions and was larger for RCP 8.5 than RCP 4.5 (Table S1). The greatest increases were exhibited in the Northern and Central Plains, while values in the Southern Plains increased appreciably only in late-century for RCP 8.5. Interannual variability of NPP simulations for each of the five climate projections was greater in the mid- and late-century periods than during the historic reference, and inter-model variability was smallest in the Northern Plains and in the Southern Plains, for both RCPs (Table S1).

The historical distribution of annual NPP in the Great Plains represented a bell curve in which 5.7 years per decade was within 25% of the 30 year mean NPP, and on average 2.2 and 2.1 years per decade had extreme NPP values that deviated greater than 25% above and below mean NPP, respectively (not shown). The Northern, Central, and Southern Plains had 4–4.7 extreme years per decade in the historical period, with the largest number occurring in the Southern Plains. Extreme years increased in all three regions in future simulations compared to the historic period. Independently of the region, the number of the future extreme years was 5.4–6.4 and 5.9–6.9 per decade for RCP 4.5 and 8.5, respectively, which represents an increase of 33%–56% and 38%–73% for RCP 4.5 and RCP 8.5, respectively (Figure 2). The number of extreme years further increased from mid- to late-century in the Southern and Central Plains, but remained constant in the Northern Plains for RCP 4.5.

The increase in the number of extreme years from mid- to late-century was greater for RCP 8.5 than for RCP 4.5, as anticipated, and a greater number occurred in mid-century for RCP 8.5 than for RCP 4.5 in late-century, in all three regions. The lowest and highest future simulation both occurred in the Northern Plains and projected 0.5 and 3.7 more extreme years per decade, respectively, compared to historic simulations based on observed climate data (Figure 2). The difference among individual NPP simulations was smaller in the Southern Plains (8.6%) than in the Northern (18.7%) and Central (17.6%) Plains (data not shown). The number of extreme years per decade did not show large differences or clear patterns between the eastern and western portions of the three regions for either historical or future simulations (data not shown).

The number of years per decade with extreme surplus and deficit NPP values was approximately equal for historical simulations at 2–2.5 in all three regions (Figure 3). However, the proportion of extreme surplus and deficit years began to diverge in the Northern and Central Plains in future simulations (Figure 3a,b). In both regions, surplus years increased more than deficit years, particularly in late-century for RCP 8.5. Surplus years in the Northern Plains increased to 3–5 per decade, while deficit years remained near the historic reference. In the Southern Plains, future extreme surplus, deficit, and near-normal years occurred in equal proportion, with approximately 3–3.5 per decade.

The difference in mean total NPP of extreme surplus and deficit years divided by the mean total NPP for each time period represents the variability that occurred among regions for the three time periods. This ratio ranged from 83% in the Central Plains to 90% in the Northern and Southern Plains for the historic period (Figure 4). This percentage increased in future simulations for both RCPs and was lowest in the Northern Plains (91%–95%) and highest in the Southern Plains (107%–119%). Similarly, the relative increase in this ratio, compared to historic values, was smaller in the Northern Plains (2%–5%) than in the Central (19%–25%) and Southern (18%–30%) Plains. The ratios remained relatively constant within a specific region in mid- and late-century for both RCPs indicating an unexpectedly high amount of interannual variability in NPP throughout the Great Plains.

The magnitude of extreme surplus and deficit years both deviated approximately 40% from mean NPP in historic simulations for all three regions (Figure 5). However, the magnitude of extreme years varied between regions in future simulations, especially in late-century for RCP 8.5. Deficit years deviated further from mean NPP in the Northern and Central Plains, while surplus years became more moderate in the Northern Plains and remained relatively constant in the Central Plains. In contrast, both deficit and surplus years deviated further from mean

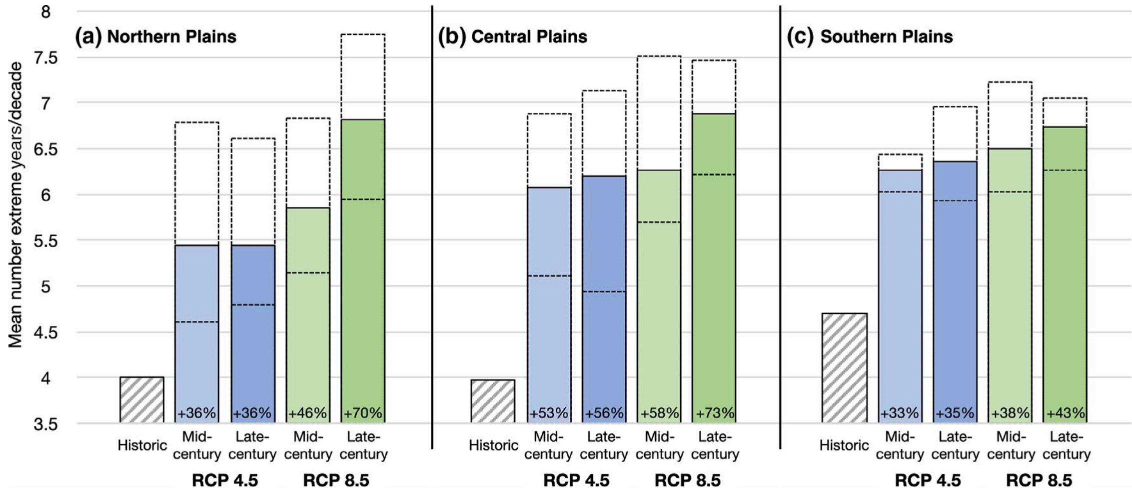


**FIGURE 2** Mean number of years per decade with NPP >±25% of the annual mean for the Northern (a), Central (b), and Southern (c) Plains for each of the three time periods. Gray striped bars represent historic simulations (1981–2010), and blue and green bars represent future simulations based on climate projections for RCP 4.5 and 8.5, respectively. Light and dark colors represent simulations for 2041–2065 (mid-century) and 2075–2099 (late-century). Colored bars represent the ensemble averages and dashed lines associated with each bar represent the lowest and highest individual model simulations. Percentages at the bottom of the colored bars show the relative increase in years per decade for the ensemble average from their respective historic reference. NPP, net primary production; RCP, representative concentration pathway [Colour figure can be viewed at wileyonlinelibrary.com]

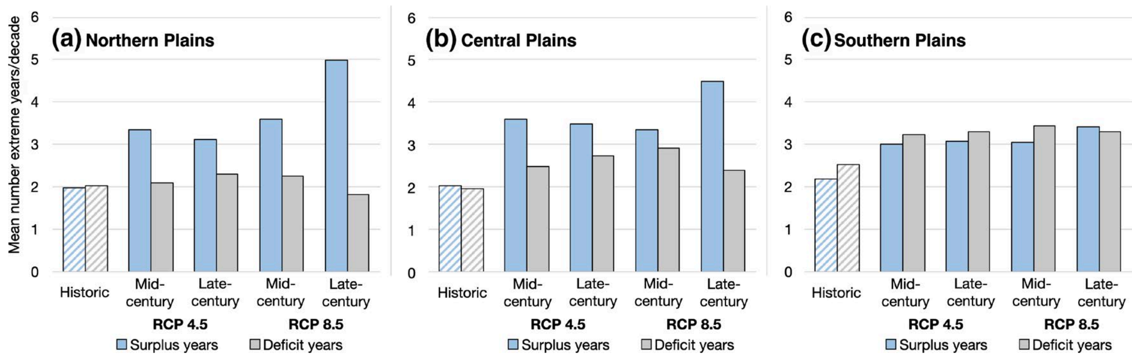


**FIGURE 3** Mean number of years per decade with extreme surplus (blue bars) and deficit (gray bars) NPP for the Northern (a), Central (b), and Southern (c) Plains. Striped bars represent the historic reference and the other four pairs represent future simulations for mid- and late-21st century for RCP 4.5 and RCP 8.5. NPP, net primary production; RCP, representative concentration pathway [Colour figure can be viewed at wileyonlinelibrary.com]

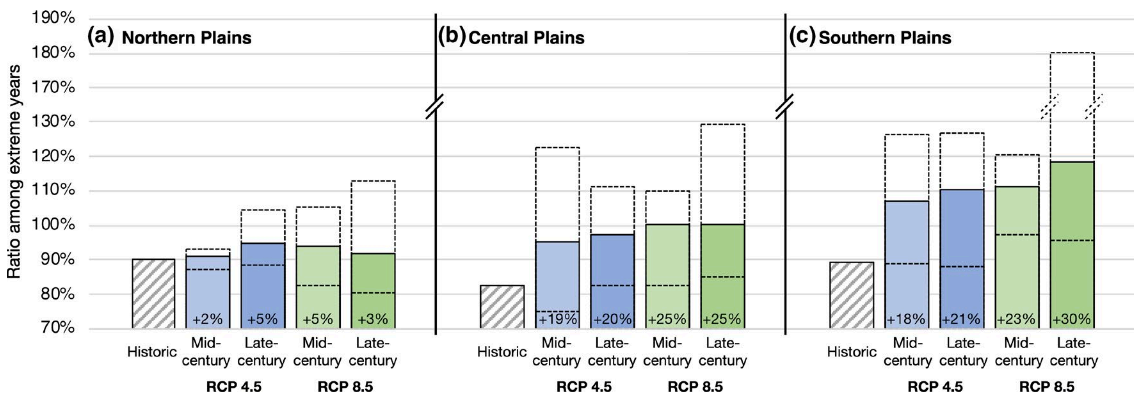


**FIGURE 4** Difference between mean NPP of extreme surplus and extreme deficit years divided by the total average NPP for the Northern (a), Central (b), and Southern (c) Plains. Gray striped bars represent the historic reference (1981–2010) and blue and green bars represent future simulations for RCP 4.5 and 8.5. Light and dark colored bars represent simulations for 2041–2065 (mid-century) and 2075–2099 (late-century), respectively. Blue and green bars show the ensemble average, dashed lines show the lowest and highest individual model simulations. NPP, net primary production; RCP, representative concentration pathway [Colour figure can be viewed at wileyonlinelibrary.com]

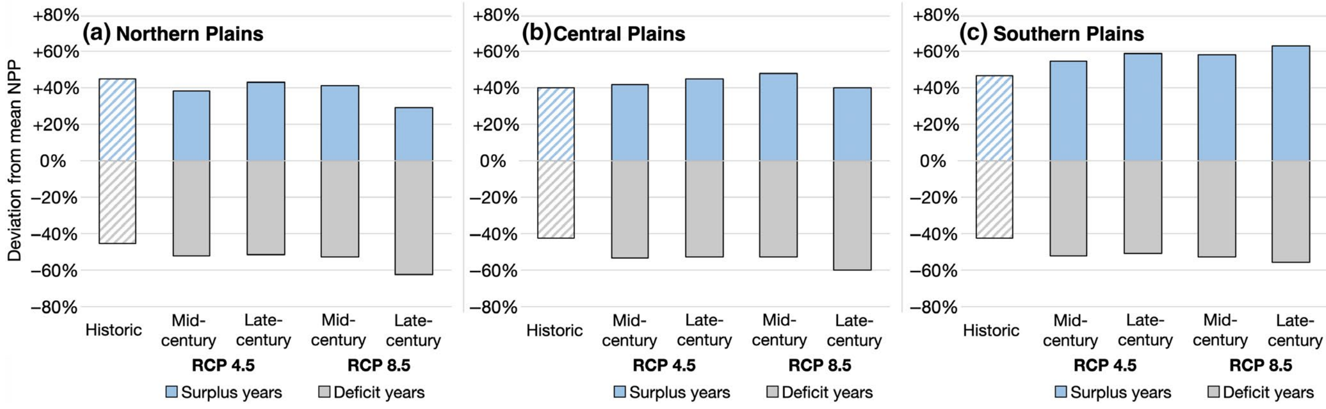


**FIGURE 5** Deviation of mean NPP in years with extreme surplus and deficit NPP relative to mean total NPP for the Northern (a), Central (b), and Southern (c) Plains. Striped bars represent the historic reference and the other four pairs represent future simulations based on mid- and late-21st century climate projections for RCP 4.5 and RCP 8.5. NPP, net primary production; RCP, representative concentration pathway [Colour figure can be viewed at wileyonlinelibrary.com]

NPP in the Southern Plains, to further increase the range of interannual NPP variability (Figure 5c).

## 4 | DISCUSSION

The results of the climate projections and NPP simulations are interpreted within a vulnerability framework where exposure represents the variability and change in future climates; sensitivity describes the frequency and magnitude of years with forage surpluses and deficits; and the limits of adaptive capacity are defined by the extent to which surplus and deficit years increase in future climates. Interaction among these three vulnerability components will determine the production capacity and economic viability of rangeland beef cattle production in future climates (Adger, 2006; Nelson et al., 2010).

Variation in interannual NPP represents a simple, but critical variable to determine the vulnerability of rangeland beef cattle production; however, it is not the only variable determining the success of beef cattle operations. These enterprises occur within complex social–ecological systems that are influenced by local, national, and global events (Irisarri et al., 2019; Wilmer et al., 2018). Enterprise sensitivity may also be indirectly influenced by land area and economic status, drought preparedness planning, and ecological condition of rangelands at the onset of drought (Haigh, Otkin, Mucia, Hayes, & Burbach, 2019; Kachergis et al., 2014; Nelson et al., 2010). Intra-annual forage variability also has important consequences for rangeland beef production (Derner, Raynor, Reeves, Augustine, & Milchunas, 2020), but MC2 model simulations of NPP only functioned on annual time steps. These broad approximations may provide the basis for more specific vulnerability assessment of rangeland beef production in future climates.

The ±25% threshold for NPP variation is a general assumption regarding the adaptive capacity of beef producers, rather than a meteorologically derived value. It assumes that the majority of current beef producers in the region could accommodate this amount of variability and remain economically viable. For comparison, NPP variation of ±25% is smaller than simulated annual mean NPP during the droughts of 1988 and 2011 in the Great Plains, which were 43% and 28%, respectively, below the 1981–2010 NPP mean. However, a threshold of economic viability is difficult to establish because it is highly dependent on the size and type of production enterprise, managerial skills, and adaptive strategies. Consequently, this NPP threshold simply provides a reference to highlight increasing inter-annual variability and its potential consequences for beef cattle production and economic viability.

### 4.1 | Exposure

Future climates will expose rangeland beef cattle production to distinctly different conditions than those experienced in the recent past in two important ways. First, MAT will increase proportionately in all three regions throughout the century and maintain the historic differences in MAT among regions. Higher MAT will increase potential evapotranspiration and decrease rain-use efficiency to reduce NPP, which may offset a temperature-induced increase of the growing season (Wehner, Arnold, Knutson, Kunkel, & LeGrande, 2017). Second, the entire region will experience a major increase in the frequency of extreme NPP years and minor changes in the magnitude of extreme years. The increase in the number of surplus years will be greatest in the Northern Plains, intermediate in Central Plains, and absent in the Southern Plains. Deficit years will exhibit the opposite trend—increases will be greatest in the Southern Plains and smallest in the Northern Plains. The magnitude of deficit years increases in all three regions, but the Southern Plains is the only region to exhibit an increase in the magnitude of both surplus and deficit years.

Drought, especially multi-year drought, has historically had the most adverse impact on beef cattle production and profitability (Bastian et al., 2006; Hamilton et al., 2016). Unfortunately, drought frequency and intensity are very difficult climate anomalies to project (Conant et al., 2018; Kloesel et al., 2018). However, several climate projections have identified an increasing risk of severe drought and increased aridity in the Central and Southern Plains as the century progresses (Cook, Ault, & Smerdon, 2015; Seager et al., 2018). Collectively, these results suggest that severe drought similar to that experienced in the region in 2011–2014 may occur with greater frequency than in the recent past.

### 4.2 | Sensitivity

Future simulations of NPP exhibit considerable variation in the magnitude and frequency of extreme surplus and deficit years among the three regions, especially for RCP 8.5. An increase in the frequency and a decrease in the magnitude of surplus years are accompanied by a constant frequency, but greater magnitude of deficit years in the Northern Plains. Climate variability in this region will be expressed as an increase in surplus years of lower magnitude interspersed with deficit years of greater magnitude. In contrast, the magnitude and frequency of both deficit and surplus years are projected to increase in the Southern Plains. Climate variability will be characterized by primarily extreme years of increasing magnitude. The sequence in which these extreme years occur will further amplify forage variability to influence cattle production and enterprise sensitivity. For example, adjacent surplus and deficit years that are +40% and −40% of mean NPP, which is similar to that observed in the historical period, would represent a variation in forage production that equals 80% of mean annual NPP. This distinction between future climates in the Northern and Southern Plains indicates that climate risk planning will need to account for the different conditions and challenges that may occur in these two regions.

Future climates may exacerbate cattle nutritional stress by reducing forage quality, in addition to the increased variability of forage production (Craine, Elmore, & Angerer, 2017; Craine, Elmore, Olson, & Tolleson, 2010). An analysis of cattle fecal chemistry samples collected in the United States revealed that increasing MAT and decreasing MAP reduced crude protein and digestible organic matter for regions with continental climates (e.g., the Great Plains; Craine et al., 2010). Similarly, the ratio of crude protein to digestible organic matter in forage was found to be 13% higher in 1994–2004 than in 2005–2015, which corresponds to a 12% increase in atmospheric $CO_2$ and a 0.34°C increase in temperature from 1994 to 2015 (Craine et al., 2017). Even though climate-induced changes in absolute forage quality are small, it was estimated that they would reduce steer growth by 13.6 kg per animal (12.5%) over a 113 day grazing period in northeastern Colorado (Augustine et al., 2018).

Major shifts in plant species composition may influence regional beef cattle production in future climates. Woodland encroachment in the Southern Plains has had a major impact on rangeland forage and livestock production beginning early last century (Wilcox et al., 2018; Wilcox, Sorice, Angerer, & Wright, 2012), and woodland encroachment is now occurring in the Central Plains (Barger et al., 2011; Briggs et al., 2005). Previous MC2 simulations indicated that total NPP may increase in the Northern Plains in response to increasing MAP and MAT, but that the increases may be greatest for woodland NPP and land cover beginning near mid-century (Klemm et al., 2020). Woody plant productivity has been observed to exceed that of herbaceous productivity following encroachment (Hughes et al., 2006) and this disproportionate productivity response may be magnified by increasing precipitation variability (Gherardi & Sala, 2015). This may further decrease regional grassland NPP in the Northern Plains, and to a lesser extent in the Central Plains in late-century. However, the response of woody plants to increasing climate variability (Gherardi & Sala, 2019), drought (Moore et al., 2016), and drought–fire interactions (Twidwell, Rogers, Wonkka, Taylor, & Kreuter, 2016) in future climates is complex and multiple outcomes are likely to be realized.

The consequences of forage deficit years on beef cattle production are well recognized (Hamilton et al., 2016); however, future climates may introduce a novel challenge associated with an increasing number of surplus years interspersed with deficit years. Intermittent surplus years will challenge beef producers to rapidly increase animal numbers to convert abundant forage into animal production. An increasing frequency of surplus forage years may decrease animal production and profit when compared to a similar amount of forage production that is more evenly distributed among years. Alternatively, surplus years could yield benefits in other ecosystem service categories, including C sequestration, water yield, and biodiversity. High interannual precipitation variability may contribute to multiple related ecological responses associated with both beneficial outcomes (i.e., vegetation recovery and soil health) and detrimental outcomes (i.e., wildfires, exotic species invasions, and soil erosion).

### 4.3 | Adaptive capacity

The capacity to effectively balance increasingly variable forage production with animal demand on a sustainable, cost-effective basis is of paramount importance to minimizing the vulnerability of beef cattle production in future climates (Haigh et al., 2019; O'Reagain, Scanlan, Hunt, Cowley, & Walsh, 2014; Shrum et al., 2018). However, evidence suggests that the majority of rangeland beef producers possess insufficient adaptive capacity to effectively contend with current climate variability (Coppock, 2011; Joyce et al., 2013; Marshall, Taylor, Heyenga, & Butler, 2018). For example, 80% ($n$ = 340) of Utah beef cattle producers surveyed self-identified as being passive or reactive managers as opposed to proactive managers (Peterson & Coppock, 2001). Increasing age, declining health, and pending retirement were the primary reasons contributing to the high incidence of passive management. Active management was associated with higher gross enterprise incomes, strong stewardship values, and a willingness to assume debt to invest in drought adaptation planning (Peterson & Coppock, 2001). Similar adaptation deficits have been documented in northern Australia where 84%

($n$ = 240) of cattle producers were characterized as being socially vulnerable to climate variability because of insufficient strategic skills required to manage risk and uncertainty (Marshall, Stokes, Webb, Marshall, & Lankester, 2014). In contrast, 60% ($n$ = 307) of Wyoming beef cattle producers had adopted proactive approaches to drought, which may have been a response to recent droughts in 2002 and 2011 (Kachergis et al., 2014).

Increasing climate variability, in conjunction with variable preparedness among producers and enterprises, establishes conditions in which future climates may overwhelm the existing adaptive capacity to adversely impact the economic viability and ecological sustainability of rangeland beef enterprises (Godde et al., 2019; Reeves et al., 2017). The majority (57%) of beef producers in the Southern Plains acknowledged that climate is changing and expressed interest in the development of climate preparedness to minimize risk (Campbell, Becerra, Middendorf, & Tomlinson, 2019). Yet, the capacity of producers to proactively minimize the sensitivity of production enterprises to climate variability is difficult to determine because it represents a complex interaction of social and ecological variables that vary greatly with the attributes of various production enterprises (Briske et al., 2015; Kachergis et al., 2014; Nelson et al., 2010).

Climate risk planning to sustain beef cattle production in the Great Plains will need to consider the sensitivity of the diverse categories of rangeland beef cattle enterprises (Joyce et al., 2013; Wilmer et al., 2018). For example, midsize enterprises (100–200 cows) may be more sensitive than either smaller or larger enterprises to increasing climate variability because large enterprises have greater adaptive capacity and resources to commit to adaptation strategies (Kachergis et al., 2014). Smaller enterprises may be less sensitive because cattle production may not represent the primary source of revenue (Peterson & Coppock, 2001). Therefore, increasing climate variability may restructure beef production enterprises throughout the Great Plains by decreasing the categories of enterprises that prove to be most sensitive, and therefore, the most vulnerable. The key challenge will be to anticipate which structural categories of beef cattle enterprises and supporting adaptive strategies will be most appropriate to maintain viable beef cattle production throughout the Great Plains in the 21st century.

Increasing climate variability and the potential for more frequent and severe droughts establishes conditions in the Central and Southern Plains that are reminiscent of the series of boom–bust cycles experienced in the Australian cattle industry during the 20th century (Stafford Smith et al., 2007). Drought events occurred on approximately 20 year intervals, and they contributed to progressive rangeland degradation because emphasis was placed on “fast variables” of immediate economic concern (e.g., forage and cattle production) while discounting “slow variables” supporting rangeland resilience (e.g., plant species composition and soil erosion). This created a mismatch between socioeconomic and climatic systems because cattle producers were unable to independently adapt to this magnitude of precipitation variability and the supporting agencies and programs were unable to respond to infrequent droughts in a timely manner. These authors concluded that successful adaptation to severe climate variation may require the involvement of multiple societal sectors to maintain economically and ecologically viable cattle production (Stafford Smith et al., 2007). These lessons, as well as those emerging from the prolonged drought in Queensland, Australia (Phelps & Kelly, 2019), may be particularly relevant to beef cattle production in the Great Plains as the century progresses.

## 4.4 | Implications

Projections of increasing interannual precipitation variability and higher temperatures, in conjunction with variable preparedness among production enterprises, demonstrate the vulnerability of rangeland beef cattle production to future climates in the Great Plains. The interannual variability of MAT is projected to increase beyond that of historical values in the Central and Southern Plains from 0.7 and 0.5°C, respectively, to ca. 0.9°C in mid- and late-century. This level of variability will approach that of the Northern Plains, which remains constant throughout the century at 1.0°C. The variability of MAP is projected to increase in all three regions, but it will be greatest in the Southern Plains where both the frequency and magnitude of forage surplus and deficit years increase. Consequently, the Southern Plains may experience the greatest increase in future climate variability, but beef cattle producers in this region have historically encountered greater climate variability than producers in the Northern and Central Plains. However, the vulnerability of rangeland beef production to increasing climate variability is difficult to assess because the limits of socioeconomic viability among the various categories of production enterprises, the willingness and ability of beef producers to independently and collectively enhance their adaptive capacity, and the future market value of beef products are largely unknown.

An extensive survey of climate risk planning and policy supporting natural resource management in the Great Plains found that climate change skepticism had delayed development and implementation (Romsdahl, Wood, & Hultquist, 2015). Insufficient recognition of the potential risk imposed by climate variability was identified as the primary cause of inaction. Inadequate climate risk planning may contribute to “crisis management” that limits social learning and development of adaptive capacity to effectively increase preparedness for future climate extremes (Haigh et al., 2019). This is exemplified by the continuation of emergency assistance programs that frequently have the unintended consequences of increasing vulnerability to subsequent drought because recipients are not required to modify their management practices or develop new management skills (Peterson & Coppock, 2001; Wilhite, Sivakumar, & Pulwarty, 2014). For example, the Livestock Forage Disaster Program funded by the U.S. Department of Agriculture, allocated \$4.4B to livestock producers in 2014 for drought losses incurred earlier in the decade (Hanberry et al., 2019). Recognition that future climates may not mimic those of the past century may represent a critical step toward the reallocation of these funds to programs and policies that promote climate preparedness throughout the region.

Development and implementation of regional climate risk planning and associated adaptation strategies may exceed the logistical, technical, and financial capacity of individual beef producers (Chambwera et al., 2014). Comprehensive, regional adaptation planning may require assistance from state and national agencies, in partnership with the private sector, to maintain economically and ecologically viable rangeland beef cattle production (Juhola, 2019; Mimura et al., 2014; Wilhite et al., 2014). The central goals of climate preparedness will be to maintain economic viability by minimizing costly destocking–restocking cycles and to prevent degradation of rangeland resources, especially soils and biodiversity, under conditions of increasing climate variability. The question becomes "who will take responsibility for the development and implementation of climate risk planning to address the pending consequences of climate variability on rangeland beef cattle production and the associated socio-ecological consequences throughout the Great Plains (Juhola, 2019)?" A multisector approach involving local, state, and national actors is currently envisioned as being the best approach to confronting a climate challenge of this magnitude (Stafford Smith et al., 2007). These regional climate planning strategies are arguably best founded on the premise of an uncertain future, rather than one of enhancing predictability of the future (Pelling, 2011).

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## CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

## DATA AVAILABILITY STATEMENT

Research data are not shared publicly but can be provided upon request.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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