# Drought Impacts on Cattle Stocking Rate and Land Use

# Introduction

Selecting an appropriate stocking rate is one of the most crucial decisions in grazing management (Smart et al. 2010). It plays a central role in determining both grazing efficiency and the long-term health of the land. Producers can optimize forage utilization, prevent overgrazing, and support the ecological resilience of pastures and rangelands. In contrast, improper stocking rates - whether too high or too low - can lead to significant land degradation, a reduction in biodiversity, and diminished livestock productivity.

There are several competing theories as to why the stocking rate might have been decreasing. First, cattle are harvested at heavier weights. Fewer feeder cattle are needed to produce the same amount of beef and thus leading to fewer cows (Figure 1). Larger animals demand significantly more forage resources (Uresk 2010). The increased size of cattle means that although fewer cows are being grazed, the forage demand per acre remains relatively high. Thus, the increase in cattle size does not fully explain the observed fluctuations in stocking rates.

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**Figure 1. US historical steer finishing weights and beef cow head numbers (2000-2024).**

Source: USDA, NASS (2024).

Second, the amount and quality of grazing land and pasture have changed. The quality of land could change particularly in the Northern Plains[[1]](#footnote-1) where good pasture that is tillable could be converted to grain production given high corn and soybean prices. This reduction in land suitable for grazing, compounded by climate change, poses additional challenges. However, advances in grazing management, such as rotational grazing systems, offer potential mitigation by increasing the land's carrying capacity (Jacobo et al. 2006), allowing producers to maintain or even enhance forage utilization on reduced acreage.

Furthermore, climate variability - marked by rising temperatures and shifting precipitation patterns - exacerbates the challenge of maintaining optimal stocking rates.

Insufficient precipitation reduces hay yields and crop residue, while excessive rainfall can lead to waterlogging, nutrient loss, and pest proliferation, all of which increase reliance on irrigated feed resources. Droughts, in particular, have intensified in both frequency and severity, posing significant risks to agricultural systems and rangeland ecosystems (Leeper et al., 2022; Iglesias, Travis, and Balch, 2022). These unpredictable climate conditions complicate the balance between stocking rates and available forage, further challenging sustainable grazing management.

While existing research has explored the broader relationships between climate variability and beef cows (Klemm and Briske, 2019; Rodziewicz, Dice, and Cowley 2023), agriculture (Kuwayama et al. 2019), change in farmland use and stocking rate (Mu, McCarl and Wein 2013), and rangeland beef cattle production (Briske et al. 2020), there is a notable gap in identifying whether temperature increases or the frequency and intensity of precipitation have a greater influence on stocking rates. This knowledge is essential for crafting more precise and effective adaptation strategies to address climate change. Understanding whether temperature increases or changes in precipitation have a greater impact on stocking rates will enable producers and policymakers to optimize management practices and allocate resources more strategically. The objective of this paper is to determine the extent to which climate variability, particularly changes in precipitation patterns such as droughts, influences stocking rates. We hypothesize that precipitation, particularly in the form of droughts, has more significant impact on forage availability and thus on stocking rates, as it leads to increased reliance on harvested feed resources like hay and irrigated crops. To test this, we employ USDA Census of Agriculture data combined with PRISM weather data, using a regression-based approach to assess the relationship between climate variables and stocking rates. We also included hay stocks as another explanatory variable for this analysis. Hay stocks provide supplemental feed when forage availability is reduced due to adverse weather conditions, such as insufficient rainfall or extreme temperatures. The model aims to capture how producers adjust their stocking rates not only in response to climate factors but also based on the availability of alternative feed sources.

We found that stocking rates are significantly influenced by both climatic factors and hay availability. Drought-related variables exhibited a delayed yet profound effect, reflecting their impact on forage availability over time. This highlights the need to incorporate lagged drought variables in predictive models to capture their long-term impact. Furthermore, we observed a nonlinear relationship between hay stocks and stocking rates, with initial increases in hay stock correlating with reductions in stocking rates but eventually becoming a stabilizing resource. Projections using the weather dataset under two climate scenarios provide insights into future stocking rate trends under varying climate trajectories, offering valuable guidance for long-term adaptive management.

This paper is organized as follows: this section is followed by literature review on the effects of climate variability on agriculture and beef production. Data and methods sections are further followed by results, discussion, including robustness analysis, and concludes with final remarks and policy implications.

# Literature review

The relationship between climate variability and beef cattle production has gained an increasing interest due to the growing frequency of extreme weather events. Klemm and Briske (2019) conducted a retrospective assessment of spatial and temporal distribution of beef cow numbers in relation to climate variability from 1978 to 2017 in the U.S. Great Plains. During droughts in the late 1980s and early 2010s, the overall number of cows declined. Authors identified the relations between beef cow numbers and mean annual precipitation (MAP) and mean annual temperatures (MAT). Higher cow numbers coincided with higher MAP values in census years. This correlation was weaker in the Northern Plains than in the Central and Southern Plains. While MAT was negatively correlated with cow numbers for all regions. These findings suggest that as climate level changes, particularly in the form of more frequent and intense droughts, regions in the Southern and Central Plains may become increasingly vulnerable to reductions in cattle production. Authors also identified a critical gap in the current understanding of the relationship between climate variability and sustainable beef production. Their findings point the need for more research on how rising temperatures and shifting precipitation patterns will continue to impact the industry, especially as their projections indicate that these trends will likely worsen over time.

Hrozencik, Perez-Quesada, and Bocinsky (2024) examined the Livestock Forage Disaster Program (LFP), US Department of Agriculture (USDA) initiative aimed at supporting livestock producers who experience forage losses due to drought or wildfire. Programs like LFP, alongside broader USDA initiatives such as the Federal Crop Insurance Program (FCIP), provide critical financial support to help stabilize farm incomes under adverse climatic conditions. The study assessed how LFP payments influence cattle herd retention decisions in drought-affected areas and evaluated the potential financial-climate risk of the program for the Federal Government under various greenhouse gas emission scenarios. The study utilized a combination of survey data, administrative records, and climate data. Specifically, it examined whether the program led to comparable outcomes in terms of livestock herd retention and liquidation between drought- affected counties eligible for LFP and those ineligible for the program. The study found that the

change in beef cattle herd size in drought-affected counties receiving LFP payments was same as to herd size changes in counties experiencing less severe drought that did not receive LFP support. Modeling results indicated that LFP payments enable beef cattle producers in drought- affected areas to make herd stocking and liquidation decisions similar to those of producers in regions facing less severe drought conditions. Under moderate and middle-range greenhouse gas emission scenarios, projections suggest that Federal Government expenditures on LFP will increase by 45% and 65% respectively, by the end of the 21st century, relative to the average expenditures between 2014 and 2022.

Rodziewicz, Dice, and Cowley (2023) provide an empirical analysis of the effects of drought on cattle herd management, hay production, prices, and farm income from 2000-2022 in the US. Using USDA CropScape Data, U.S. Drought Monitor (USDM), and a panel regression framework with fixed effects, authors concluded that drought significantly reduces hay production and increases hay prices. It leads to herd liquidation and temporarily higher revenues for ranchers but ultimately resulting in lower farm incomes. The results show that a one-unit increase in drought intensity results in a 1% decrease in herd size, 1% increase in farm revenues, 4% decrease in income, 12% decline in hay production and 5% increase in hay prices.

The paper highlights the financial vulnerability of cattle ranchers due to the limited use of federal livestock insurance programs, suggesting that expanding these programs could help mitigate the adverse economic effects of drought. Additionally, the paper highlights the regional variability in drought impacts, with the western Plains and southwestern U.S. experiencing the most severe reductions in herd sizes and hay production.

Mu, McCarl and Wein (2013) explore how U.S. agricultural producers are adapting to climate change, particularly through changes in land use and cattle stocking rates. Authors examine how climate variability, especially rising temperatures and fluctuating precipitation, has influenced the balance between crop and pasture land and, consequently, the stocking rate for cattle across different regions of the U.S. The analysis relies on USDA Census of Agriculture and National Climatic Data Center (NCDC) data. Projections revealed that there will be a 6% decrease in cropland and a 33% increase in pastureland by the end of the century. The relation between higher precipitation intensity and stocking rate is negative. Authors found that as summer temperature increases and precipitation decreases, stocking rate decreases. The Central and Southeastern U.S. are projected to experience the largest reductions in stocking rates, as these areas are more susceptible to extreme heat and drought conditions. This study contributes to the understanding of how agricultural systems in are adapting to climate change, particularly in terms of land use and livestock management.

Ritten et al. (2010) examined optimal stocking decisions on rangelands in the context of unpredictable weather patterns and climate change impacts. Using a stochastic dynamic programming (SDP) model, they analyzed how varying stocking rates could help producers maximize profitability while accounting for fluctuations in precipitation and forage growth. Unlike traditional models that rely on constant, average weather assumptions, this model incorporates weather variability, allowing stocking rates to adapt to actual growing season conditions. The SDP model treats rangeland management as a bioeconomic process in which stocking decisions impact forage availability, animal performance, and profitability. This dynamic framework enables producers to make decisions that maximize long-term financial returns while ensuring the sustainability of rangeland resources. Under climate scenarios, the model shows that producers would need to reduce stocking rates to maintain rangeland sustainability, although this adaptation could lead to reduced profitability and greater fluctuations in livestock weights. This feature demonstrates the importance of adjusting stocking rates in response to both favorable and unfavorable conditions, as climate change amplifies variability in rangeland environments. Their findings also suggest that policies should promote flexible stocking rates that adapt to seasonal conditions, allowing producers to mitigate the financial and environmental risks associated with increased drought and other extreme weather events.

Existing research often touches on the effects of climate variability more generally but does not thoroughly explore how drought events - both in terms of frequency and intensity - affect the stocking rate itself, which is a critical metric for managing pasturelands and ensuring sustainable cattle production. Our study aims to fill this void by focusing specifically on the direct impact of drought on stocking rates.

# Data

## Stocking rate

In order to estimate cattle stocking rate, first we retrieve county level beef cow inventory data and pastureland data from USDA Census of Agriculture for the period 1982-2017[[2]](#footnote-2) (USDA 2024). Figure 2 illustrates historical trends in pastureland use and beef inventory data (as of the end of December) across the United States. It can be seen that while beef cow inventory has shown some fluctuations over the years, with notable declines observed around 1983, 2012, and 2018, pastureland use has exhibited a steady decline.

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**Figure 2. Annual US national beef cow inventory and pastureland data.**

Source: USDA, NASS (2024).

The stocking rate is commonly expressed as the number of Animal Units (AU) or Animal Unit Months (AUM) per unit of land (Redfearn and Bidwell 2017). AU is defined as a mature cow weighing approximately 1,000 pounds, while AUM represents the amount of forage required to sustain one AU for one month. The total forage demand is calculated by multiplying the number of AUs by the grazing duration (in months), resulting in the total AUMs required for the grazing period. Using this methodology, the stocking rate (expressed in AUMs per acre) for a specific county and year can be derived using the following formula:

The formula incorporates three key factors: the number of animals (inventory), their forage demand, and the land resources. The term  converts the forage requirements of animals with varying sizes into a standardized measure based on an AU. By adjusting for grazing duration (months) and dividing by the size of the available pastureland, the stocking rate reflects both the available forage quantity and the grazing duration[[3]](#footnote-3).

## Drought data

Drought mechanisms are driven by a complex interplay of climatic, hydrological, and ecological factors that influence water availability in ecosystems. A key aspect of drought is the imbalance between water supply, largely determined by precipitation, and water demand, influenced by temperature, vegetation, and atmospheric conditions. Understanding drought requires quantifying these components, particularly evapotranspiration, which represents the loss of water through evaporation and transpiration. To construct a drought indicator, potential evapotranspiration (PET) is estimated, representing the amount of water that could be evaporated under current weather conditions. Using the Thornthwaite method (Palmer and Havens 1958, 123):

where is a monthly normative potential evapotranspiration value (mm ); is the monthly average temperatures (); is an annual heat index; is a monthly heat index; is a constant. Afterwards, we calculate a measure of the water surplus or deficit for the analyzed month as follows:

where is a monthly precipitation level (mm ). Daily weather data, for the period of interest, is retrieved from Parameter-elevation Regressions on Independent Slopes Model (PRISM), which provides high-resolution, gridded climate data, including precipitation, temperature (minimum, maximum, and mean), and other weather-related variables across the US (PRISM Climate Group, Oregon State University 2024).

## Weather data

Now, we turn to weather data, which plays a central role in understanding both drought dynamics and crop growth conditions. While precipitation drives water supply, temperature is a critical factor influencing plant development through thermal time accumulation and heat stress. Growing Degree Days (GDD) and Extreme Degree Days (EDD) are widely used metrics for quantifying these thermal effects on crops. GDD measures the accumulation of daily thermal time (DTT) above a base temperature, capturing the growth potential for plants, while EDD accounts for periods of extreme heat that may harm crop development. Using PRISM data, we calculate GDD and EDD following established methodologies (Zhou and Wang 2018):

where , is base temperature and is upper threshold temperature. The critical threshold temperatures of 10 and 31 are chosen for this analysis[[4]](#footnote-4) (Schlenker and Roberts 2009). These metrics allow us to assess both the beneficial and adverse effects of temperature on agricultural systems, offering valuable insights into the interaction between climate variability and ecosystem productivity.

## Hay stocks

During drought conditions, pasture growth is significantly limited, reducing the availability of forage for grazing. This compels producers to rely on hay as supplemental feed to maintain livestock health and productivity. Incorporating hay stocks into the analysis captures the critical role of supplemental feeding in mitigating the adverse effects of drought, offering a more comprehensive perspective on the relationship between drought, forage availability, and stocking rates. For this study, we utilize annual nationwide hay stocks data from USDA NASS (2024) for the period of interest, providing a robust dataset to assess the role of supplemental feeding during periods of forage scarcity.

## Summary statistics

Table 1 provides a detailed breakdown of stocking rates by region[[5]](#footnote-5) and decade across the continental United States, highlighting both national and regional trends. The Northern Plains experienced a sharp decline, dropping from 0.80 AUMs per acre in the 1980s to 0.43 in the 2020s. Similarly, the Mountain region exhibited persistently low rates likely reflecting limited grazing capacity. In contrast, the Lake States demonstrated remarkable growth, increasing from 0.58 AUMs per acre in the 1980s to 1.33 in the 2020s, with a notable 40.27% rise between the 2000s and 2010s. While regions like the Pacific and Southern Plains maintained relatively stable but low rates during these times, other regions showed greater sensitivity, reflecting differences in resilience and management practices. These results suggest that, despite a gradual national recovery in stocking rates, regional disparities underscore the complex interplay between drought, forage availability, and grazing capacity, warranting further investigation into the relationship between drought and stocking rates.

**Table 1. Stocking rate by US geographical region, 1990-2020.**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Region | Year | | | | Percent Change (%) | | |
| 1980-1989 | 1990-1999 | 2000-2009 | 2010-2019 | 1990-1980 | 2000-1990 | 2010-2000 |
| Appalachia | 1.1 | 1.4 | 1.37 | 1.43 | 27.43 | -2.01 | 3.83 |
| Corn Belt | 1.1 | 1.18 | 1.34 | 1.53 | 7.69 | 13.15 | 14.68 |
| Delta States | 1.02 | 1.12 | 1.08 | 1.22 | 9.49 | -3.22 | 13.21 |
| Lake States | 0.58 | 0.71 | 0.95 | 1.33 | 23 | 33.33 | 40.27 |
| Mountain | 0.17 | 0.2 | 0.15 | 0.16 | 12.64 | -22.6 | 2.87 |
| Northeast | 0.58 | 0.74 | 0.75 | 1.02 | 28.15 | 1.36 | 34.74 |
| Northern Plains | 0.8 | 0.7 | 0.42 | 0.43 | -12.04 | -40.48 | 1.82 |
| Pacific | 0.27 | 0.3 | 0.28 | 0.29 | 9.39 | -4.86 | 1.18 |
| Southeast | 0.97 | 1.05 | 0.93 | 1.09 | 7.93 | -11.5 | 17.29 |
| Southern Plains | 0.32 | 0.34 | 0.34 | 0.3 | 7.32 | -1.47 | -11.52 |
| National | **0.69** | **0.77** | **0.76** | **0.88** | **12.03** | **-1.68** | **15.41** |

Source: USDA NASS (2024) and authors' calculations.

# Methodology

We employ a panel regression model to analyze the impact of climate variables and hay stock on the stocking rate across counties. The dependent variable is the natural logarithm of the stocking rate (*.* By transforming the stocking rate into its logarithmic form, we aim to account for the non-linear relationship between stocking rates and the explanatory variables, while facilitating interpretation in terms of percentage changes.

where Drought (​) captures the influence of water deficits or surpluses, calculated as the difference between precipitation and PET. Weather () integrates GDD and EDD. These variables account for climatic variations that directly affect the health and productivity of grazing land. Hay stock is modeled with both linear () and quadratic () terms to capture potential diminishing returns or other non-linear effects. During drought or forage scarcity, hay serves as a critical supplemental feed. Including both terms allows the model to reflect how incremental increases in hay stock may provide less benefit at higher levels, providing insights into optimal feeding strategies. Finally, the fixed effects (​) account for unobserved heterogeneity across counties and years[[6]](#footnote-6). County-level fixed effects control for time-invariant factors such as soil quality and geographic features, while year fixed effects capture time-specific trends like economic shocks or climate anomalies. By including these controls, the model ensures that the estimated effects of climate variables and hay stock are not biased by confounding factors. This comprehensive approach provides a robust framework to analyze how climatic factors and feed availability interact to influence stocking rates. It highlights the importance of supplemental feeding strategies and the role of climatic variability in shaping livestock management decisions.

# Results

Table 2 reports the regression results. Across all models, the coefficient for  is positive and statistically significant, indicating that drought conditions, as measured by water deficit or surplus, play a critical role in influencing stocking rates. Specifically, a one-unit increase leads to a percentage increase in stocking rates ranging from 0.034% (Model 1) to 0.062% (Model 4). This suggests that favorable drought conditions, such as periods of water surplus, enable ranchers to sustain higher stocking rates (more AUMs per acre) by supporting forage availability. The results further suggest that more days with favorable growing conditions (GDD) contribute positively to stocking rates by promoting pasture growth and forage availability. The coefficient for EDD is negative and statistically significant in all models where it is included. A one-unit increase in EDD leads to a decrease in stocking rates, ranging from 0.807% (Model 3) to 0.541% (Model 5). This suggests that exposure to extreme heat conditions negatively impacts stocking rates, likely due to heat stress on livestock and reduced forage productivity.

In Model 4, the coefficient for hay stocks is negative and statistically significant. The negative coefficient for hay stock indicates that as hay stock increases, stocking rates tend to decrease. This might initially seem counter intuitive. The result could reflect the use of hay as a supplement during drought or periods of reduced forage availability. When forage conditions are poor, ranchers may rely more heavily on hay, reducing the number of cattle that can be grazed directly on pasture. This finding suggests that higher hay stock might act as a buffer during poor grazing conditions, allowing ranchers to maintain some level of production. Furthermore, results suggest a non-linear relationship between hay stock and stocking rates. Initially, as hay stock increases, stocking rates decline (as indicated by the linear term), but beyond a certain point, further increases in hay stock actually support higher stocking rates. The effect of hay stock is minimized when it is approximately 2,038,710 tons. Beyond this point, the effect of hay stock begins to increase again due to the quadratic nature of the relationship. This again highlights the complexity of hay stock's role in moderating the adverse effects of climatic variability.

The adjusted  values remain relatively high across all models, ranging from 0.76 to 0.79. However, the within  is considerably lower (e.g., 0.020 in Model 1 to 0.137 in Model 5), suggesting that much of the variation in stocking rates is explained by between-group differences rather than within-group variation. The inclusion of year fixed effects in Models 1 through 3 helps capture unobserved time-specific shocks, whereas their exclusion in Models 4 and 5 allows for direct assessment of the hay stock variables.

**Table 2. Regression analysis results.**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Variable | (1) | (2) | (3) | (4) | (5) |
|  | 0.00034\*\*\* | 0.00039\*\*\* | 0.00035\*\*\* | 0.00062\*\*\* | 0.00044\*\*\* |
|  |  | 0.00631\*\*\* | 0.00713\*\*\* | 0.01404\*\*\* | 0.01301\*\*\* |
|  |  |  | -0.00807\* | -0.00350 | -0.00541\* |
|  |  |  |  | -0.00011\*\*\* | -0.00712\*\*\* |
|  |  |  |  |  | 0.00001\*\*\* |
| County FE | Y | Y | Y | Y | Y |
| State FE | Y | Y | Y | Y | Y |
| Year FE | Y | Y | Y | N | N |
|  | 0.79 | 0.79 | 0.79 | 0.76 | 0.77 |
|  | 0.020 | 0.028 | 0.029 | 0.103 | 0.137 |
| N | 18,595 | 18,595 | 18,595 | 18,595 | 18,595 |

Source: Authors’ calculations.

Note: \*\*\* p < 0.01, \*\* p < 0.05, and \* p < 0.10.

# Robustness check

## Delayed effects of drought

Droughts can impact stocking rates in both immediate and long-term ways, with their effects often lagging behind the onset of drought conditions. Klemm and Briske (2019) highlight that the full impact of drought may not be immediately reflected in ranchers' decisions, as drought often causes a gradual depletion of forage resources. Initially, ranchers may rely on hay reserves or supplemental feed to sustain their herds, temporarily masking the effects of reduced forage availability. This reliance on reserves can delay the need to adjust stocking rates, particularly during the early stages of a drought when supplemental feed is still accessible and relatively affordable. However, as drought conditions persist, the gradual depletion of hay stocks and the increasing costs of replenishing them can force ranchers to reduce stocking rates to prevent overgrazing and long-term degradation of their pastureland. These reductions in stocking rates may be further exacerbated by the lingering impacts of drought on pasture recovery. Even after normal precipitation resumes, pastures often require time to regenerate, leading to prolonged periods of reduced forage productivity. Such delayed effects mean that the influence of a drought can extend well beyond its immediate duration, creating ongoing challenges for ranchers in balancing herd sizes with the long-term health of their pasture ecosystems.

To account for these potential lagged effects, this study will incorporate lagged variables of drought-related climate measures. By doing so, we aim to capture the full extent of drought's influence on stocking rates over time, refining our analysis and providing a more comprehensive understanding of how drought impacts livestock management decisions. This approach recognizes that both immediate and belated drought effects play a critical role in shaping grazing strategies and herd management practices, emphasizing the importance of long-term planning for sustainable pasture use.

We first observe that lagged values of ( exhibit significant correlations across multiple years. This suggests that the effects of drought in one year may persist and influence conditions in subsequent years. For instance, a water deficit in one year may reduce pasture quality and soil moisture, carrying over effects to the next grazing season. Conversely, a surplus might provide delayed benefits such as improved forage availability. To account for these interdependencies and cumulative effects, we use Principal Component Analysis (PCA). PCA allows us to summarize the information from the current drought variable and its lagged values ( …) into a single uncorrelated index (the principal component​). This index captures the shared variance among the drought variables, representing their combined or cumulative effect. We intend to reduce multicollinearity and simplify interpretation, focusing on the overall drought intensity and persistence across multiple years rather than individual contributions from each lag.

We use the first principal component derived from the current drought variable and its lagged values. The first component is chosen as it explains most of the variance among drought variables. Considering that drought effects typically persist for several years, we include up to 5 lagged years in the analysis, consistent with observed drought durations in many regions. Table 3 summarizes the regression results for models incorporating 1 to 5 lagged drought years. Each model evaluates the cumulative impact of drought conditions (represented by PC1), alongside other key variables. Fixed effects are also included to account for time-invariant regional characteristics and broader trends.

**Table 3. Regression results for delayed drought effects.**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Variable | 1 Lag | 2 Lags | 3 Lags | 4 Lags | 5 Lags |
| PC1 | 0.11311\*\*\* | 0.10876\*\*\* | 0.12521\*\*\* | 0.11774\*\*\* | 0.11020\*\*\* |
|  | 0.01001\*\*\* | 0.01170\*\*\* | 0.011884\*\*\* | 0.01110\*\*\* | 0.01073\*\*\* |
|  | -0.00299 | -0.00707\* | -0.00797\*\* | -0.01259\*\*\* | -0.01587\*\*\* |
|  | -0.00586\*\*\* | -0.00584\*\*\* | -0.00638\*\*\* | -0.00606\*\*\* | -0.00632\*\*\* |
|  | 0.00000\*\*\* | 0.00000\*\*\* | 0.00000\*\*\* | 0.00000\*\*\* | 0.00000\*\*\* |
| County FE | Y | Y | Y | Y | Y |
| State FE | Y | Y | Y | Y | Y |

Source: Authors’ calculations.

Note: \*\*\* p < 0.01, \*\* p < 0.05, and \* p < 0.10.

It is important to note that we cannot distinctly identify which specific year of drought contributes most to the observed effects, as our approach captures only the cumulative impact across multiple lagged years. Nevertheless, the findings strongly indicate that lagged drought effects exist and significantly influence grazing systems. However, to fully understand the role of individual years and their contributions to the cumulative impact, future studies must address these gaps. Collecting more granular annual data on stocking rates, as well as additional contextual variables, would help disentangle the effects of specific drought years.

## Threshold effects

Pasture thresholds for temperature effects can be distinct from those observed in row crops like corn or soybeans due to differences in physiological responses and growth patterns. According to Schlenker and Roberts (2009), temperature has a nonlinear relationship with crop yields, with specific thresholds marking optimal and stress ranges. Authors identify these thresholds by modeling temperature's marginal effects on crop yields, using piecewise regressions with temperature bins and dummy variables to capture nonlinearities. The paper divides temperature into distinct segments (or "bins") and calculated how incremental temperature changes affected log-yields. The temperature ranges were derived from extensive yield and climate data, where thresholds were chosen based on empirical evidence of where temperature begins to hinder growth. The final analysis is conducted at the county level, allowing for the aggregation of yields and temperature effects while controlling for fixed effects to account for unobserved heterogeneity across locations.

To adapt this approach for hay, we will follow the exact methodology described in the paper and apply it specifically to Douglas County, Kansas, using hay data sourced from USDA NASS (2024). We will use the same temperature binning method to identify the thresholds for hay growth and stress. By leveraging the same regression framework with temperature dummies, we aim to assess whether hay exhibits similar temperature thresholds as row crops or if its growth patterns diverge significantly, as might be expected given the perennial and resilient nature of many forage species. The Figure 3 illustrates the marginal effects of temperature on hay yield (log-transformed, tons/acre) across a range of temperatures. At lower temperatures (below approximately 31°C), the marginal effects remain relatively flat, indicating stable hay yields within this range. Beyond 31°C, the marginal effects begin to decline sharply, showing a marked reduction in hay yields as temperatures approach and exceed 35°C. This drop signifies the onset of heat stress, where critical physiological processes like photosynthesis, water uptake, and cellular respiration are adversely affected.

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**Figure 3. Marginal effects of temperature on hay yield (Douglas County, Kansas).**

Source: USDA, NASS (2024). Authors’ calculations.

The analysis supports the validity of 31°C as the upper temperature threshold used in our regression model. By selecting 31°C as the threshold in our model, we are effectively capturing this critical transition point, ensuring that the piecewise regression accurately reflects the temperature-yield relationship for hay.

## Stocking rate projections

This study utilizes climate projection data from the Multivariate Adaptive Constructed Analogs (MACA) datasets to project future stocking rates under Representative Concentration Pathways (RCP) 4.5 and RCP 8.5 scenarios, which are part of the Coupled Model Intercomparison Project Phase 5 (CMIP5). The MACA dataset provides high-resolution (4-km grid) downscaled climate data, which was extracted and aggregated at the county level across the United States. RCP 4.5 represents a stabilization scenario where radiative forcing is stabilized at 4.5 W/m² by the year 2100 through the implementation of mitigation measures, while RCP 8.5 reflects a high-emissions "business-as-usual" trajectory, leading to radiative forcing of 8.5 W/m² (Multivariate Adaptive Constructed 2024). The weather variables analyzed include monthly precipitation, minimum temperature, and maximum temperature, spanning the years 2006 to 2099. These variables were processed for both scenarios to calculate derived agroclimatic indices critical for understanding forage growth and livestock productivity. Incorporating CMIP5 scenarios allows this study to provide a robust comparative analysis of future stocking rate dynamics, capturing the implications of moderate (RCP 4.5) versus severe (RCP 8.5) climate change trajectories. The results aim to inform adaptive grazing management strategies and policy interventions to enhance livestock system resilience in a changing climate.

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**Figure 4. Projected stocking rates (2020-2099).**

Source: MACA weather projections and Authors’ calculations.

Figure 4 illustrates the projected stocking rates across the United States from 2020 to 2099 under the RCP 4.5 and 8.5 climate scenarios. A comparative analysis of the two scenarios highlights subtle differences in the trends. While both scenarios show significant inter-annual variability, RCP 4.5 demonstrates a relatively stable trajectory with periodic increases, suggesting that mitigation efforts leading to stabilized radiative forcing could sustain better forage conditions for livestock productivity. In contrast, RCP 8.5 shows sharper declines in some years, reflecting the stress on grazing systems caused by more extreme climate conditions under high emissions. Notably, the gap between the two scenarios widens over time, particularly in the latter half of the century (2070–2099), underscoring the cumulative impact of high emissions on livestock systems. Despite these variations, the results suggest a broadly consistent long-term trend across both scenarios, emphasizing the resilience of livestock systems when supported by adaptive management practices. However, the slight divergence in stocking rates between the scenarios underscores the potential benefits of mitigation efforts to stabilize climate impacts and maintain sustainable livestock operations. This analysis provides a critical foundation for understanding the interplay between climate change and livestock systems, offering insights into how different climate trajectories may influence grazing capacity. These findings are instrumental in informing policy decisions and adaptive strategies aimed at enhancing the resilience of livestock systems under changing climatic conditions.

# Discussions

The results of this study provide valuable insights into the complex relationships between climate variability, hay stock, and cattle stocking rates. Our findings confirm that both favorable and extreme weather conditions, as well as forage availability, are critical factors in determining the stocking capacity of pastureland. These results align with earlier studies that identified climate as a key driver of grazing management decisions (Klemm and Briske, 2019; Mu et al., 2013), but this research adds specificity by quantifying the direct effects of water deficits, temperature extremes, and forage availability on stocking rates. This finding also resonates with the conclusions of Rodziewicz et al. (2023), who observed that extreme weather conditions often lead to herd reductions and economic strain on ranchers. While the results are well-established in existing literature, the strength and direction of these relationships in our analysis add valuable nuance.

## Policy implications

The findings of this study reinforce the importance of adaptive grazing practices that account for delayed drought impacts. Policies should incentivize ranchers to adopt strategies such as flexible stocking rates, rotational grazing, and pasture resting periods. These practices can mitigate the long-term degradation of pasturelands and support their recovery after drought events. Offering financial incentives or technical support to ranchers who implement these practices can help bridge the gap between short-term economic needs and long-term sustainability goals.

Programs like the USDA's Livestock Forage Disaster Program (LFP) have demonstrated their value in mitigating the immediate economic impacts of drought on ranchers. However, projections indicate that with increased drought frequency and intensity under the high-emission RCP 8.5 scenario, federal expenditures on such programs are expected to rise significantly. Policymakers should consider refining the eligibility criteria and payment structures of programs like the LFP to enhance their fiscal sustainability while ensuring they target the most affected regions effectively. Additionally, integrating disaster assistance programs with broader climate adaptation frameworks, including early-warning systems and localized weather projections, can further strengthen the resilience of livestock systems.

Another key area for policy intervention is the management of forage and hay stocks. Our findings highlight the diminishing marginal returns of hay stock during periods of drought, emphasizing the importance of efficient hay management practices. Policymakers should incentivize investments in hay storage infrastructure, forage improvement programs, and market mechanisms to stabilize hay prices. These measures can help reduce the economic burden on ranchers and prevent overreliance on supplemental feeding, which is often unsustainable during prolonged drought periods.

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1. Northern Great Plains region of the USA includes the states of Colorado, Montana, Nebraska, North Dakota, South Dakota, and Wyoming (USDA n.d.). [↑](#footnote-ref-1)
2. The Census of Agriculture reports come out every 5 years. [↑](#footnote-ref-2)
3. For example, suppose a pasture is used to graze 50 animals, each weighing 1,200 pounds, for six months. Assuming a standard AU represents 1,000 pounds, each animal equates to 1.2AUs. If the pastureland is 100 acres, the stocking rate is 3.6 AUMs per acre. [↑](#footnote-ref-3)
4. Robustness analysis section analyses different threshold values for pasturelands and their impacts on results. [↑](#footnote-ref-4)
5. Regions are grouped based on shared geography, climate, and agriculture. The Lake States (Michigan, Wisconsin, Minnesota) focus on dairy and forage, while the Corn Belt (Iowa, Illinois, Indiana, Ohio, Missouri) leads in grain and livestock feed. The Northern and Southern Plains emphasize beef cattle, with differences in grazing and irrigation. The Delta States and Southeast combine crop cultivation and cattle operations, while Appalachia supports small-scale farming. The Northeast features diversified farming and dairy, the Mountain region specializes in large-scale grazing, and the Pacific excels in diverse, high-value agriculture, with California pivotal for irrigated forage and beef cattle production. These regional adaptations highlight the diversity of U.S. agriculture. [↑](#footnote-ref-5)
6. We assume that the fixed effects control for time-invariant factors (e.g., soil quality and geographic features), uniform shocks across years (e.g., national economic trends), and input costs. [↑](#footnote-ref-6)