**Formatted for: Environmental Research Letters**

*Last updated: June 30, 2025*

**Climate Variability and Drought Effects on Cattle Stocking Decisions**

Shara Akat1\*, Taro Mieno1, Elliott Dennis1

1 Department of Agricultural Economics, University of Nebraska – Lincoln

\*Corresponding Author Information

Shara Akat

205D Filley Hall

University of Nebraska-Lincoln

Lincoln, NE 68583

Email: [sakat2@husers.unl.edu](mailto:sakat2@husers.unl.edu)

# Keywords: drought, cattle, stocking rate, hay stocks, climate variability

# Abstract

Cattle stocking rate is a key decision in grazing management, influencing forage use, ecosystem resilience, and rangeland sustainability. This study investigates how drought conditions and hay availability affect stocking rates across the U.S. Using county-level panel data from 1982 to 2022, we estimate a fixed-effects model incorporating current and lagged drought indices, agroclimatic variables, and hay stocks. Results show that water deficits significantly reduce stocking rates, with effects persisting into the following year. Lower hay stocks are also associated with reduced stocking, indicating producers adjust stocking intensity in response to feed constraints. We project future stocking rates under CMIP6 climate scenarios (RCP 4.5 and 8.5) through 2099. Projections show gradual declines under RCP 4.5 and sustained reductions under RCP 8.5, especially after mid-century. These findings highlight the vulnerability of grazing systems to climate change and the need for adaptive management to maintain livestock productivity. We further quantify how these projected changes in stocking rates could reshape beef cow inventories, production capacity, and drought assistance demands offering critical insights for long-term resilience planning across the U.S. beef industry.

# Introduction

Stocking rate is a key decision in grazing management, affecting forage use, ecological resilience, and the long-term sustainability of rangelands (Smart et al., 2010; Holechek, 1988). Optimal stocking prevents overgrazing, while inappropriate rates, either too high or too low, can lead to land degradation, biodiversity loss, and reduced livestock productivity (National Drought Mitigation Center, n.d.; Redfearn and Bidwell, 2017).

Recent evidence shows a long-term decline in cattle stocking rates, with more land now being required per cow to sustain grazing (Dennis, 2021). This trend potentially reflects a combination of factors, including increased cattle weights, shifting land use driven by crop prices, and most notably, climate variability. Rising temperatures and altered precipitation patterns have emerged as key drivers, disrupting forage growth and feed availability (Mu, McCarl, and Wein, 2013). Insufficient rainfall reduces hay and crop residue yields, while excessive precipitation can cause waterlogging, nutrient leaching, and increased dependence on irrigated feed. Intensifying droughts further complicate stocking decisions, undermining both ecological stability and economic resilience (Leeper et al., 2022; Iglesias et al., 2022). Given these dynamics, our aim is to better understand how weather variability, particularly drought, affects cattle stocking rates.

Several studies have examined how climate variability influences cattle production. DeLay, Mooney, and Ritten (2025) show that climate extremes reduce overall U.S. beef cow inventories and shift herd distribution toward smaller operations, highlighting herd downsizing as a key adaptation strategy. Klemm and Briske (2019) conducted a retrospective analysis of temporal and spatial distributions of beef cow populations relative to climate variability from 1978 to 2017 across the U.S. Great Plains. Their findings indicate that cattle numbers correlate positively with precipitation and negatively with temperature. Patalee and Tonsor (2021a) found that average temperature during the growing season (April-July) significantly increased beef cow inventories due to improved forage growth, while higher precipitation during colder months (October-March) reduced inventories. Their spatial analysis also revealed positive spillover effects across neighboring counties, underscoring the influence of seasonal weather and geographic clustering on cow-calf production. In a complementary state-level study, Patalee and Tonsor (2021b) further emphasized that extreme temperatures during key breeding months significantly impact cow-calf inventories, with heat stress reducing reproductive performance. They also demonstrated that incorporating seasonal weather data substantially improves the accuracy of long-term inventory forecasts. Rodziewicz, Dice, and Cowley (2023) employed an econometric framework to analyze drought impacts on beef cattle management, hay production, prices, and farm incomes from 2000 to 2022. Using USDA CropScape data, U.S. Drought Monitor information, they demonstrated that drought events reduced hay production, increased hay prices, and ultimately decreased income from cattle operations. Mu, McCarl, and Wein (2013) similarly explored adaptations by U.S. agricultural producers to climate change, focusing on land-use changes and cattle stocking rates. Their results indicated that as the summer Temperature-Humidity Index increases and summer precipitation decreases, cattle stocking rates decline with projected reductions of 10-15% under future climate scenarios due to rising temperatures and the conversion of cropland to pastureland. Ritten et al. (2010) further emphasized optimal stocking decisions on rangelands, stressing flexible management practices to mitigate financial risks posed by extreme weather and drought. While previous studies have provided valuable insights into how droughts and temperature variability affect production, cattle sales, and farm income, this study extends the existing literature by integrating multiple detailed drought indicators. Specifically, our analysis explicitly accounts for both immediate drought impacts and delayed effects carried over from preceding years, simultaneously incorporating hay stock data as a measure of supplemental feeding availability. This approach enables a more dynamic and realistic assessment of drought’s influence on cattle stocking rates, capturing the dynamic responses producers adopt in managing forage scarcity.

This study combines USDA Census of Agriculture data with Parameter-elevation Regressions on Independent Slopes Model (PRISM) weather records to examine how climate stress indicators influence cattle stocking rates. We use Potential Evapotranspiration (PET), Growing Degree Days (GDD), and Extreme Degree Days (EDD) to assess water stress, heat exposure, and thermal pressure on grazing systems. Through an econometric framework, we quantify how drought severity affects producer decisions and propose adaptive management strategies to support sustainable livestock production. Our measure of drought severity is defined as the monthly water deficit, calculated as the difference between Potential Evapotranspiration (PET) and total precipitation.

Our findings indicate that stocking rates are significantly influenced by both current and lagged drought conditions, as well as hay availability. Water deficits, whether experienced in the current year or the year prior, consistently reduce stocking rates, highlighting the persistent effects of drought stress. Additionally, we find that lower hay stocks reduce stocking intensity, likely reflecting producers’ precautionary responses to limited feed reserves. Our projections of stocking rate reveal that under a moderate emissions pathway, it declines gradually, whereas high-emissions scenarios lead to a more pronounced and sustained reduction in grazing capacity. These findings underscore the importance of adaptive grazing strategies and feed security planning to sustain livestock production under increasing climate variability.

**Data**

## Stocking Rate

County-level beef cow inventory and pastureland acreage data are obtained from the USDA Census of Agriculture from 1982-2022[[1]](#footnote-1) (USDA 2024). Figure 1 illustrates the national trends in pastureland area and beef cattle inventory as of December of each census year. Over time, beef cow inventory has fluctuated, with notable declines observed around 1983, 2012, and 2018, while pastureland use has exhibited a steady decline. These reductions in cow numbers reflect a combination of structural and environmental factors, including increased carcass weights of finished steers, which allow producers to achieve the same or greater beef output with fewer animals, as well as cyclical herd dynamics and weather-related variability (Luke, Anderson, and Tonsor 2022; Patalee and Tonsor 2021a). The latter includes drought events and seasonal climate extremes, both of which influence producers’ decisions regarding herd expansion, retention, and culling (Patalee and Tonsor 2021a; Rodziewicz, Dice, and Cowley 2023).

A graph with lines and numbers

AI-generated content may be incorrect.

**Figure 1. US national beef cow inventory and pastureland by census year, 1982-2022.**

Source: USDA (2024).

Stocking rate is commonly expressed in terms of Animal Units (AU) or Animal Unit Months (AUM) per unit area, where one AU represents a mature cow weighing approximately 1,000 pounds, and one AUM signifies the forage required to sustain one AU for one month (Redfearn and Bidwell, 2017). To quantify total forage demand, the total number of AUs is multiplied by the grazing duration, which we set to 5 months, resulting in the total AUMs required for a specified grazing period. Thus, stocking rate, expressed as AUMs per acre, is calculated for each county and year as follows:

This formula incorporates three key variables: livestock inventory, animal forage demand, and the available pastureland. Specifically, the term standardizes forage requirements based on average cattle weight and grazing duration. We assume that cattle can graze any time between March and October with a total grazing duration of 5 months (). Adjusting forage demand by total pasture area ensures the stocking rate accurately reflects both forage availability and land capacity constraints.[[2]](#footnote-2)

Cow live weight is estimated using national cow carcass weights from USDA and an industry average 55% dressing percentage (South Dakota State University 2024). To align with the annual frequency of the beef cow inventory and pastureland data, we aggregate monthly slaughter weight data to the annual level. These annual data are sourced from USDA NASS Livestock Slaughter reports for the period 1978-2022 and compiled by the Livestock Marketing Information Center (USDA NASS 2025).

## Weather Data

Drought occurrence and severity are driven by complex interactions between climatic, hydrological, and ecological factors affecting water availability within ecosystems (Srivastava and Maiya, 2023). A central feature of drought is the imbalance between water supply (primarily driven by precipitation) and water demand (driven by temperature, vegetation, and atmospheric conditions). Accurately quantifying drought conditions requires metrics capturing both the evaporation and plant transpiration processes (Granger, 1989). To develop drought indicators, we estimated Potential Evapotranspiration (PET), a measure representing the maximum rate at which water could evaporate under ideal moisture conditions. PET was computed using the Thornthwaite method (Palmer and Havens 1958):

where is a monthly normative potential evapotranspiration (mm ); is the monthly average temperature (); is an annual heat index; is a monthly heat index; and is a constant. To assess water balance, precipitation data is integrated with PET to calculate the water surplus or deficit for each month:

where is a monthly precipitation level (mm ). For the econometric analysis, these monthly values are aggregated to the annual level by summing them over the grazing season (March through October), consistent with typical forage growth and livestock management periods (Voth 2020; University of Nebraska-Lincoln, 2024).

Temperature significantly influences cattle inventory by affecting both pasture conditions and crop growth (Patalee and Tonsor 2021a). While precipitation reflects water supply, high temperatures compound drought impacts by reducing water availability and amplifying plant water stress (Srivastava and Malix, 2023). We quantify these impacts by incorporating Growing Degree Days (GDD) and Extreme Degree Days (EDD), widely recognized metrics for assessing thermal impacts on crops (Spinoni, Vogt, and Barbosa 2015). GDD captures the accumulation of thermal time (DTT) above a base temperature, reflecting growth potential (Zhou and Wang 2018), while EDD measures exposure to extreme heat detrimental to forage productivity (Huang, Sassenrath, and Lin 2023). Following Zhou and Wang (2018), these indices are defined as follows:

where , is base temperature and is upper threshold temperature. Given the absence of well-established cardinal temperature thresholds for pasture or rangeland species, we adopt generalized thresholds of 12°C and 31° as representative values, based on the mid-range thresholds reported across major crops (Luo 2011).

Collectively, PET, GDD, and EDD offer an integrative view of weather impacts, encapsulating water availability, thermal stress, and heat exposure. We calculated these and other weather-related variables across the United States using PRISM data.

## Hay Stocks

Hay stocks serve as a critical supplemental feed source when grass forage availability is limited by drought conditions. Reduced pasture growth during droughts restricts grass forage production, necessitating supplemental feed sources (Moore et al. 2003). Incorporating hay stocks assesses how supplemental feeds mitigate drought-induced impacts on forage availability and grazing management decisions proxied by cattle stocking rates. Recent evidence shows that hay prices increase significantly with drought severity, underscoring the rising importance of hay as forage conditions deteriorate (Rowley 2023). We utilize annual national hay stocks data from USDA NASS (2024) from 1982-2022.[[3]](#footnote-3)

## Summary Statistics

The summary statistics presented in Table 1 provide a breakdown of stocking rates in the U.S. by geographic region[[4]](#footnote-4) across five decades (1970s-2010s), highlighting notable national and regional trends (USDA ERS 2000). Nationally, stocking rates increased modestly from 0.65 AUMs per acre in the 1970s to 0.95 AUMs per acre in the 2020s, reflecting an overall growth of approximately 46.15% during this period.

Regional trends exhibit considerable variability. The Northern Plains region experienced a marked decline, with stocking rates dropping from 0.80 AUMs per acre in the 1980s to 0.38 AUMs per acre in the 2020s, representing a nearly 53% decrease. Similarly, the Mountain region consistently exhibited low stocking rates, fluctuating narrowly between 0.15 and 0.40 AUMs per acre, likely indicating limitations in grazing capacity or constraints due to environmental conditions. In contrast, the Lake States demonstrated remarkable growth, increasing from 0.46 AUMs per acre in the 1970s to 1.52 in the 2020s. Meanwhile, regions like the Pacific and Southern Plains exhibited relatively stable patterns and consistently low stocking rates. The Pacific region experienced a modest increase of approximately 11%, while the Southern Plains saw a notable decline of around 48%, reflecting opposite yet gradual long-term trends.

These varied regional trajectories underscore persistent geographical disparities and emphasize the complexity of factors influencing stocking rates including forage availability, climate stress, grazing practices, and economic drivers. Understanding these patterns provides essential context for evaluating stocking rate adjustments and developing targeted management and policy responses to mitigate drought impacts and enhance agricultural sustainability.

**Table 1. Stocking rate by US region, 1980-2020.**

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Region | Periods | | | | | | Percent Change (%) | | | | |
| 1970s | 1980s | 1990s | 2000s | 2010s | 2020s | 1980s-1970s | 1990a-1980s | 2000s-1990s | 2010s-  2000s | 2020s-2010s |
| Appalachia | 1.13 | 1.09 | 1.40 | 1.37 | 1.43 | 1.53 | -2.80 | 27.43 | -2.01 | 3.83 | 7.43 |
| Corn Belt | 1.03 | 1.09 | 1.18 | 1.34 | 1.53 | 1.65 | 6.44 | 7.69 | 13.15 | 14.68 | 7.92 |
| Delta States | 0.85 | 1.02 | 1.12 | 1.08 | 1.22 | 1.23 | 20.04 | 9.49 | -3.22 | 13.21 | 0.71 |
| Lake States | 0.46 | 0.58 | 0.71 | 0.95 | 1.33 | 1.52 | 26.16 | 23 | 33.33 | 40.27 | 14.68 |
| Mountain | 0.40 | 0.17 | 0.19 | 0.15 | 0.16 | 0.13 | -56.29 | 12.64 | -22.6 | 2.87 | -15.19 |
| Northeast | 0.33 | 0.58 | 0.74 | 0.75 | 1.02 | 1.32 | 77.51 | 28.15 | 1.36 | 34.74 | 29.46 |
| Northern Plains | 0.54 | 0.79 | 0.70 | 0.42 | 0.43 | 0.38 | 47.38 | -12.04 | -40.48 | 1.82 | -9.37 |
| Pacific | 0.27 | 0.27 | 0.29 | 0.28 | 0.29 | 0.30 | -0.73 | 9.39 | -4.86 | 1.18 | 6.26 |
| Southeast | 1.02 | 0.97 | 1.05 | 0.93 | 1.09 | 1.18 | -4.88 | 7.93 | -11.5 | 17.29 | 8.22 |
| Southern Plains | 0.46 | 0.32 | 0.34 | 0.34 | 0.29 | 0.24 | -30.33 | 7.32 | -1.47 | -11.52 | -17.26 |
| National | **0.65** | **0.69** | **0.77** | **0.76** | **0.88** | **0.95** | **6.47** | **12.03** | **-1.68** | **15.41** | **8.24** |

Source: USDA (2024) and authors' calculations.

Note: Each decadal period reflects the average stocking rate based on USDA Census of Agriculture data collected during census years within that decade. Specifically, the 1970s include the census year 1978; the 1980s include 1982 and 1987; the 1990s include 1992 and 1997; the 2000s include 2002 and 2007; the 2010s include 2012 and 2017; and the 2020s reflect the single available year, 2022.

Table 2 reports pairwise Pearson correlations among the main explanatory variables. The correlation between current and one-year-lagged indices is moderate (0.62), suggesting temporal persistence in drought without excessive multicollinearity. Climatic stress variables Growing Degree Days () and Extreme Degree Days () are highly correlated reflecting overlapping temperature dynamics yet remain statistically distinguishable in the regression framework. Correlations between hay stocks and all climatic variables are low (|r| < 0.10), indicating that feed availability captures a distinct management dimension not strongly tied to current-year weather outcomes.

**Table 2. Pearson correlation matrix for variables used in stocking rate model**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Variable |  |  |  |  |  |
|  | 1.00 |  |  |  |  |
|  | 0.62 | 1.00 |  |  |  |
|  | 0.14 | 0.25 | 1.00 |  |  |
|  | 0.49 | 0.50 | 0.71 | 1.00 |  |
|  | -0.01 | 0.00 | -0.07 | -0.05 | 1.00 |

Source: Authors' calculations.

# Econometric Methods

Drought impacts stocking rates both immediately and over extended periods, reflecting short-term responses and delayed management adjustments by livestock producers. Klemm and Briske (2019) emphasize that drought effects might lag behind the actual onset of drought conditions, as ranchers’ responses and forage availability do not immediately reflect changing environmental conditions. Initially, producers may rely on hay reserves or supplemental feed to sustain their herds, temporarily delaying necessary adjustments to stocking rates. However, as drought conditions persist, the depletion of hay stocks and the rising costs of replacement feed may force producers to reduce number of grazing animals to prevent overgrazing and long-term pasture degradation (Hart and Carpenter 2001). Even after normal precipitation resumes, pastures often require extended periods to recover from drought effects further prolonging forage availability and thus stocking rates.

To capture both immediate and delayed drought impacts, our analysis employs a one-year-lagged climate-related variables indicative of water availability, specifically the water deficit or surplus variable . Our empirical investigation utilizes a panel fixed-effects model specified as follows:

where the dependent variable is the natural logarithm of the stocking rate[[5]](#footnote-5) for county and year . The independent variables include the current water deficit or surplus variable and its one-year-lagged value reflecting delayed drought conditions, Growing Degree Days (), Extreme Degree Days (), and hay stocks (). The model also incorporates county-level fixed effects () to control for unobserved, time-invariant heterogeneity, such as soil type, topography, and geographic characteristics, thus ensuring robust estimation results. This 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 3 presents the estimated effects of drought and climatic stressors on cattle stocking rates. To evaluate the robustness of estimated drought effects on stocking rates, we estimate a sequence of five fixed-effects models. Each model incrementally adds additional variables: beginning with water deficit and lagged water deficit (Models 1-2), then including GDD (Model 3), EDD (Model 4), and hay stock availability (Model 5). Across all model specifications, the coefficients on both the current and one-year-lagged water deficit or surplus variable, measured over the March-October growing season, are negative and statistically significant. The coefficients are also very stable across different model specifications. This finding provides strong evidence of both immediate and delayed effects of drought conditions on stocking decisions. The negative sign indicates that lower water availability, whether concurrent or lagged, is associated with reduced stocking rates, likely reflecting limited forage productivity and grazing capacity during and following drier periods.

**Table 3. Regression analysis results.**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Variable | (1) | (2) | (3) | (4) | (5) |
|  | -0.0007\*\*\* | -0.0005\*\*\* | -0.0006\*\*\* | -0.0005\*\*\* | -0.0005\*\*\* |
|  |  | -0.0003\*\*\* | -0.0004\*\*\* | -0.0004\*\*\* | -0.0004\*\*\* |
|  |  |  | 0.0080\*\*\* | 0.0119\*\*\* | 0.0117\*\*\* |
|  |  |  |  | -0.0297\*\*\* | -0.0298\*\*\* |
|  |  |  |  |  | -0.0003\*\*\* |
|  |  |  |  |  |  |
|  | 0.62 | 0.63 | 0.65 | 0.65 | 0.66 |
|  | 0.07 | 0.10 | 0.14 | 0.14 | 0.16 |
| N | 16,116 | 16,116 | 16,116 | 16,116 | 16,116 |

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

According to the preferred specification (Model 5), each unit decrease in water availability (measures in millimeters (mm)) leads to approximately a 0.05% decrease in stocking rate. For instance, a 100 mm decrease in water availability (e.g., transitioning from moderate to drier years) corresponds to an approximate 5% reduction in stocking rate, substantial in a management context where marginal forage losses are highly valued. This interpretation aligns with the positive and significant coefficient observed for Growing Degree Days (GDD), indicating that increased accumulation of GDD, reflective of favorable growing conditions, positively influences stocking rates. Specifically, a higher number of days with optimal temperature conditions supports pasture productivity and enables higher grazing capacities. In contrast, the coefficient for Extreme Degree Days (EDD) is consistently negative and statistically significant across all model specifications, underscoring the detrimental impact of excessive heat conditions on stocking rates. Specifically, a one-unit increase in EDD corresponds to a decrease in stocking rates of approximately 2.98%.

Further, the regression results indicate that lower hay stock levels reduce cattle stocking rates, consistent with producers’ precautionary responses to feed constraints. Each unit decrease in hay stocks (measured in 1,000 tons) reduces cattle stocking rates by 0.03%. When hay inventories decline, producers face greater constraints in managing forage shortfalls, prompting reductions in grazing intensity to preserve ecological and economic stability. This behavior likely reflects both intentional destocking and lingering effects of drought-induced feed limitations.

We conducted robustness checks to evaluate the sensitivity of our results to alternative definitions of the grazing period and grazing season. Specifically, we varied the total duration of grazing (4,5,6,7,8) and the length of the seasonal five-month grazing window (e.g., March-July, April-August, May-September) to test whether changes in climatic exposure affect the estimated effects. The magnitude of coefficients remained stable across different grazing durations, indicating that only the scale of the dependent variable shifted, while the causal relationships were preserved. Although some coefficients changed slightly when the seasonal timing of the five-month window was adjusted, the overall direction and statistical significance of key variables, particularly drought and hay stock indicators, remained consistent. These results suggest that our findings are not driven by any specific seasonal definition of grazing (see Appendix A for detailed results).

## Stocking Rate Projections

This study employs climate projections from the Coupled Model Intercomparison Project Phase 6 (CMIP6), obtained via the Earth System Grid Federation (ESGF, 2024) data portal. The dataset includes simulations under Representative Concentration Pathways (RCP) 4.5 and 8.5, representing moderate and high-emissions scenarios, respectively. These projections are derived from the CanESM5 (Canadian Earth System Model version 5), developed by the Canadian Centre for Climate Modelling and Analysis (CCCma), and have been downscaled for regional analysis (Earth System Grid Federation, 2025).

RCP 4.5 assumes a stabilization pathway in which radiative forcing is maintained at 4.5 W/m² by 2100 through mitigation measures. In contrast, RCP 8.5 follows a high-emissions trajectory, leading to 8.5 W/m² radiative forcing, assuming continued reliance on fossil fuels with minimal mitigation efforts. This study incorporates monthly precipitation, minimum temperature and maximum temperature from 2020 to 2099, to derive agroclimatic indices such as GDD, EDD, and PET. To account for inter-model variability, outputs from ten ensemble members (r01 through r10) are used for each model realization within CMIP6, enabling an ensemble-based assessment of stocking rate projections under different climate scenarios.

A graph showing the growth of the year

AI-generated content may be incorrect.

**Figure 2. Projected cattle stocking rates (AUMs per acre) (2020-2099).**

Source: Earth System Grid Federation (2025) weather projections and Authors’ calculations.

Figure 2 presents projected cattle stocking rates across the United States from 2020 to 2099 under RCP 4.5 and RCP 8.5, based on CMIP6 climate projections from the ESGF. Under RCP 4.5 (blue line), stocking rates exhibit a gradual declining trend over the century. While the decrease is moderate, it suggests that even under a mitigation pathway, forage conditions may slowly deteriorate, possibly due to residual climate stressors despite overall stabilization. Nonetheless, the relatively slow rate of decline implies that forage availability may remain sufficient to support grazing systems in the near to mid-term.

In contrast, RCP 8.5 (red line) shows a pronounced and sustained decline in stocking rates, especially after mid-century. This pattern reflects the compounded impacts of extreme heat, increased drought frequency, and declining forage productivity under a high-emissions scenario. The results are consistent with expectations that intensified climate stress will substantially reduce grazing capacity and limit sustainable stocking levels (Mu, McCarl, and Wein 2013).

# Discussion

The results of this study provide valuable insights into the complex relationships between climate variability, hay stock availability, and cattle stocking rates. Our findings confirm that both favorable and extreme weather conditions, alongside supplemental feed resources, play a critical role in shaping the stocking capacity of pastureland. These results align with prior literature identifying climate as a key driver of grazing management decisions (Klemm and Briske, 2019; Mu et al., 2013; Patalee and Tonsor 2021a, Patalee and Tonsor 2021b). However, this study advances the field by explicitly quantifying both the immediate and lagged effects of water deficits, temperature extremes, and forage availability on stocking rates. These findings are also consistent with DeLay, Mooney, and Ritten 2025 and Rodziewicz et al. (2023), who documented that extreme weather events often result in herd reductions and financial strain for ranchers. While prior studies have broadly examined the implications of climate variability for livestock systems, our analysis offers a more detailed perspective by capturing the persistence of drought impacts through lagged climatic indicators. Moreover, the use of multiple climate realizations strengthens the robustness of these results, ensuring that our projections reflect a range of plausible future conditions.

Looking forward, climate projections reveal diverging trajectories under RCP 4.5 and RCP 8.5 scenarios. Under RCP 4.5, stocking rates decline modestly, suggesting that mitigation and gradual climate shifts may allow producers to sustain relatively stable grazing systems. In contrast, the sharp and continuous decline in stocking rates under RCP 8.5 reflects compounding stressors, heat, drought frequency, and declining forage productivity, that significantly constrain long-term grazing capacity. These results underscore the vulnerability of cattle systems to climatic extremes and the need for adaptive management frameworks that incorporate forward-looking climate risks. Future work should examine how seasonal precipitation timing, forage species turnover, and producer-level adaptation strategies influence stocking trajectories. Expanding this analysis to include multi-model projections and alternative emission scenarios will further strengthen our understanding of sustainable livestock management under climate change.

## Implications

Beef Industry

Our projections of declining stocking rates under future climate scenarios potentially significant challenges for the U.S. beef industry. In 2022, the national beef cow inventory stood at 29.21 million head, supported by 430.26 million acres of pastureland. With an average cow weight of 1,350 pounds and a five-month grazing season, the baseline stocking rate was 0.46 AUMs per acre. By 2099, stocking rates are projected to decrease to 0.43 AUMs per acre under RCP 4.5 and 0.25 AUMs per acre under RCP 8.5 due to climate-driven reductions in forage productivity. To explore the implications, we analyze two counterfactual scenarios, fixed pastureland or fixed beef cow inventory, and evaluate an adaptation strategy involving reduced cow weights.

Under a fixed pastureland scenario (430.26 million acres), the beef cow herd would contract to 27.3 million head under RCP 4.5 and 15.9 million head under RCP 8.5 by 2099. This reduction translates to a decline in finished cattle output from 21.68 million head in 2022 to 20.26 million under RCP 4.5 and 11.79 million under RCP 8.5 (Table 4).[[6]](#footnote-6) Consequently, beef production would fall, requiring carcass weights to increase by 60 lbs. under RCP 4.5 or 730 lbs. under RCP 8.5 to maintain current retail beef production levels. Such increases in carcass weight are manageable for feedlots and cattle to achieve under RCP 4.5 but not under RCP 8.5.

Alternatively, maintaining a fixed beef cow inventory of 29.21 million head would necessitate pastureland, or its equivalent, to expand to compensate for reduced stocking rates. Pastureland requirements would rise to 458.5 million acres under RCP 4.5 and 788.7 million acres under RCP 8.5. Given the limited availability of additional grazing land, this scenario would likely require increased reliance on supplemental feed or land-use changes, such as converting cropland to pasture or relying on more vertical farming for forage production. However, as cow numbers remain constant, beef production would be unchanged, stabilizing supply but potentially at higher production expenses.

A key factor contributing to declining stocking rates is the historical increase in mature beef cow weights, which have risen significantly over the past 40 years. As an adaptation strategy, we assess the impact of reducing average cow weight from 1,350 lbs. to 1,150 lbs., holding productivity parameters constant. With fixed pastureland, lighter cows would allow cow inventories to expand to 32.00 million head under RCP 4.5 and 18.70 million head under RCP 8.5. This increase increases finished cattle to 13.19 million and 7.71 million head, respectively, partially offsetting production declines. However, to maintain current beef production levels, carcass weights would need to decrease to 797 lbs. under RCP 4.5 or increase to 1,362 lbs. under RCP 8.5. In contrast, with a fixed cow inventory and lighter cow weights, reduced forage demand would decrease pastureland needs to 390.60 million acres under RCP 4.5 and 671.83 million acres under RCP 8.5. This reduction in land requirements could alleviate pressure on grazing resources, allowing beef production to remain constant without altering carcass weights. This strategy highlights the potential of adjusting animal characteristics to enhance resilience to climate constraints.

We estimate long-run price impacts across the beef supply chain by applying sector-specific elasticities to projected changes in quantity under alternative climate scenarios. Under RCP 8.5 with fixed pastureland, feeder cattle prices are projected to increase from $168.83/cwt to $271.11/cwt, reflecting a 60.6% increase due to reduced calf supplies. Similarly, fed cattle prices rise from $145.73/cwt to $271.40/cwt, a 86.2% increase, driven by constrained feedlot inventories. Retail beef prices increase from $7.59/lbs to $12.75/ lbs, a 68% jump, reflecting reduced beef output and tight supply conditions.

Comparing across scenarios, we observe that reducing beef cow weights, while holding pastureland constant, allowed producers to support larger cow inventories under climate stress. For instance, under RCP 8.5 with fixed pastureland, reducing cow weights from 1,350 lbs to 1,150 lbs enabled the herd size to increase. This adjustment helped mitigate inventory losses and, as a result, dampened price increases throughout the supply chain. Specifically, feeder cattle prices rose less sharply (from $168.83/cwt to $249.38/cwt, a 47.7% increase) compared to the scenario with standard weights (which saw a 60.6% increase). Similarly, fed cattle and retail beef prices experienced more moderate increases. These findings suggest that management practices such as reducing cow weights can serve as a partial buffer against climate-induced productivity losses, thereby lessening market disruptions and price volatility under constrained forage conditions.

These findings underscore the complex interplay among cow weight, stocking rates, and pasture availability in shaping the future of U.S. beef production. Climate-induced reductions in forage availability threaten herd sizes, beef supply, and economic stability. While historical productivity gains have mitigated some land and climate challenges, sustained industry performance will depend on strategic adaptations. Reducing cow weights offers a viable approach to balance forage demand and production goals, but broader efforts such as improved grazing management, supplemental feed strategies, and policy support for land-use adjustments will be critical to ensuring the long-term viability of the beef sector under intensifying climate pressures.

Government Programs

The USDA’s Livestock Forage Disaster Program (LFP) provides direct payments to offset drought-related losses. According to Hrozenick and Perez-Quesada (2025), LFP payments have limited behavioral impact, as they do not meaningfully influence producers’ adaptation strategies or reduce vulnerability to forage shortfalls. Under a high-emissions scenario (SSP5–8.5), the authors project that annual LFP payments could exceed $1.9 billion by 2100. Their projections assume fixed production levels and static producer behavior, focusing exclusively on drought intensity. However, our stocking rate projections under RCP 8.5 show steep decline and a potential 83% increase in pastureland requirements if inventory remains fixed. These behavioral responses suggest that the LFP payment estimates by Hrozenick and Perez-Quesada (2025) likely represent an upper bound and that actual payments could be significantly lower.

To illustrate these dynamics, we apply the regression coefficients from Hrozenick and Perez-Quesada (2025) in combination with our projected beef cow inventories under various climate scenarios to estimate the resulting LFP payments. We find that payments decline considerably under RCP 8.5 conditions due to substantial reductions in beef cow inventories and pasture carrying capacity. For instance, estimated LFP payments fall from $1.08 billion under baseline 2022 conditions to as low as $0.59 billion under RCP 8.5 when pastureland remains fixed (see Table 4). These results underscore that behavioral adaptation could substantially reduce the fiscal exposure of the LFP program.

Further, our findings indicate that hay, or supplemental feed in general, serves as a critical buffer during drought. Producers who do not use supplemental feed are more likely to reduce stocking rates when hay is scarce, even under similar drought conditions. In contrast, adaptive strategies such as increased reliance on hay can help stabilize herd sizes and, consequently, LFP payments. This behavioral response highlights how access to supplemental feed can mitigate climate-induced production shocks and moderate the fiscal burden of the LFP under future scenarios.

Together, these findings indicate that climate change will likely introduce greater variability in both fiscal and land use pressures on the LFP. Adapting program triggers to better reflect key behavioral drivers, especially hay and forage availability, could improve program effectiveness and ensure stronger alignment with producer responses under future drought conditions.

**Table 4. Climate Implications on the Beef Industry Through Changes in Stocking Rate**

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Variable | Units | 2022 | Fixed  Pastureland | | Fixed Cow  Inventory | | Smaller Beef Cows Weights  With: | | | |
| **Fixed Pastureland** | | **Fixed Cow**  **Inventory** | |
| RCP 4.5 | RCP 8.5 | RCP 4.5 | RCP 8.5 | RCP 4.5 | RCP 8.5 | RCP 4.5 | RCP 8.5 |
| *Cow-Calf Sector* |  |  |  |  |  |  |  |  |  |  |
| Stocking Rate | AUMs/acre | 0.46 | 0.43 | 0.25 | 0.43 | 0.25 | 0.43 | 0.25 | 0.43 | 0.25 |
| Pastureland | mil. acres | 430.26 | **430.26** | **430.26** | 458.5 | 788.7 | **430.26** | **430.26** | 390.00 | 671.83 |
| Beef Cows | mil. head | 29.21 | 27.3 | 15.9 | **29.21** | **29.21** | 32.00 | 18.70 | **29.21** | **29.21** |
| Beef Cow Weight | lbs. | 1350 | 1350 | 1350 | 1350 | 1350 | **1150** | **1150** | **1150** | **1150** |
| Feeder Calves Borna | mil. head | 24.08 | 22.51 | 13.11 | 24.08 | 24.08 | 26.38 | 15.42 | 24.08 | 24.08 |
| Feeder Calves Soldb | mil. head | 21.68 | 20.26 | 11.79 | 21.68 | 21.68 | 23.75 | 13.88 | 21.68 | 21.68 |
| *Feedlot Sector* |  |  |  |  |  |  |  |  |  |  |
| Finished Cattlec | mil. head | 21.68 | 20.26 | 11.79 | 21.68 | 21.68 | 23.75 | 13.88 | 21.68 | 21.68 |
| Finished Cattle Carcass Weight | lbs. | 873 | 873 | 873 | 873 | 873 | 873 | 873 | 873 | 873 |
| *Retail Sector* |  |  |  |  |  |  |  |  |  |  |
| Beef Productiond | mil. lbs. (retail equivalent) | 13,245.02 | 12380.89 | 7204.869 | 13248.65 | 13248.65 | 14513.62 | 8482.07 | 13248.65 | 13248.65 |
| Carcass Weight – Indifferencee |  | - | 933  (+60) | 1605  (+732) | 873  (+0) | 873  (+0) | 797  (-76) | 1362  (+489) | 873  (+0) | 873  (+0) |
| *Price Impacts*f |  |  |  |  |  |  |  |  |  |  |
| Feederg | $/cwt | 168.83 | 183.50 | 271.11 | 168.83 | 168.83 | 147.47 | 249.38 | 168.83 | 168.83 |
| Fedh | $/cwt | 145.73 | 163.73 | 271.40 | 145.73 | 145.73 | 162.64 | 270.10 | 185.17 | 185.17 |
| Retail Beefi | $/lbs | 7.59 | 8.04 | 12.75 | 7.59 | 7.59 | 7.02 | 11.09 | 7.59 | 7.59 |
| *LFP payments*j | | | | | | | | | | |
| Payments | $ billion | 1.08 | 1.01 | 0.59 | 1.08 | 1.08 | 1.18 | 0.69 | 1.08 | 1.08 |

Note: We assume 5 grazing months and grazing period from March to October throughout; We also use fixed herd productivity assumptions of a calving rate of 85%, 3% calf mortality, and a 50:50 sex ratio with 20% heifer retention.

a) feeder calves born is estimated as: beef cow inventory \* 0.85 \* (1-0.03).

b) feeder calves sold is estimated as: feeder calves born \* (0.5 + 0.5 \* (1-0.2)).

c) Finished cattle inventory is estimated as: beef cow inventory \* 0.85 \* (1-0.03) \* (0.5 + 0.5 \* 0.8).

d) Beef production is estimated as: finished cattle inventory \* carcass weight \* 0.7 (adjusted by a retail conversion factor of 0.7).

e) Carcass weight indifference is estimated as: 13,245.02 (target beef production) / (finished cattle inventory \* 0.7).

f) We assume following long run price demand elasticities for each sector: feeder cattle -0.754, fed cattle -0.529 and retail beef -1.173 (Pendell, et al. 2010).

g) Oklahoma National Stockyards Feeder Cattle report (AMS 1280), USDA AMS (2022a). For feeder cattle, we assume a weight of 750 lbs and use the 2022 baseline of 21.68 million head. Percentage changes in quantity are calculated based on projected feeder calves sold under each scenario.

h) Texas-Oklahoma-New Mexico Monthly Weighted Average Cattle Report, Total all grades (Live FOB) (USDA AMS 2022b). We assume carcass weights of 873 lbs for standard cattle and 748 lbs for smaller cattle. Using the 2022 baseline of 21.68 million finished cattle, we estimate percentage changes in quantity based on projected head counts under each scenario.

i) Historical monthly price spread data for beef, pork, broilers (USDA ERS 2022). We assume a baseline beef production level of 13,245.02 million pounds and calculate quantity changes relative to this benchmark for each scenario.

j) LFP payments are estimated using the regression-based coefficient estimates reported by Hrozenick and Perez-Quesada (2025), as outlined in Appendix J of their study, assuming three months of LFP eligibility.

Source: Authors’ calculations.

# Conclusion

This study quantifies how drought conditions and hay availability shape cattle stocking rates across the U.S., revealing that both current and lagged moisture deficits, as well as low hay stocks, significantly reduce stocking intensity. These effects reflect producers’ behavioral responses to forage constraints and indicate that drought impacts persist beyond a single season. Projected stocking rates under climate change scenarios show consistent declines through 2099, with steeper reductions under RCP 8.5. These long-term trends suggest increasing pressure on the forage base and the need for strategic adaptation to maintain rangeland productivity.

We assessed the implications of our findings to the beef industry showing how future reductions in stocking capacity could affect meat availability to consumers. While increasing carcass weights could partially offset herd reductions, our analysis shows that maintaining current output levels under future stocking constraints would require biologically implausible high harvest weights. This underscores a key physical limitation: while genetic and nutritional advances may improve growth efficiency, cattle size cannot scale indefinitely (Maples, Lusk, and Peel 2016). Consequently, strategies to maintain production must focus on system-level mitigation, including improved pasture management, soil health, drought-tolerant forage species, and grazing flexibility.

These findings reinforce the importance of integrating long-term adaptation into both management and policy. While existing programs like the LFP provide critical short-term relief, they must evolve to account for persistent climate risks and feed-related constraints identified in this study. A forward-looking approach that supports ecological resilience and forage risk reduction will be essential for sustaining livestock production under increasing climate stress (Bastian et al. 2023).

# References

Bartley, Rebecca, Brett N. Abbott, Afshin Ghahramani, Aram Ali, Rod Kerr, Christian H. Roth, and Anne Kinsey-Henderson. 2023. “Do Regenerative Grazing Management Practices Improve Vegetation and Soil Health in Grazed Rangelands? Preliminary Insights from a Space-for-Time Study in the Great Barrier Reef Catchments, Australia.” *The Rangeland Journal* 44 (4): 221–246. <https://doi.org/10.1071/RJ22047>.

Bastian, Christopher T., John P. Hewlett, Kelly R. Creppel, and Bridger Feuz. 2023. *Ranchers Diverse in Their Drought Management Strategies*. University of Wyoming Extension B-1405. <https://wyoextension.org/publications/html/B1405/>.

Byrnes, Ryan C., Danny J. Eastburn, Kenneth W. Tate, and Leslie M. Roche. 2018. “A Global Meta-Analysis of Grazing Impacts on Soil Health Indicators.” *Journal of Environmental Quality* 47 (4): 758–765. https://doi.org/10.2134/jeq2017.08.0313.

DeLay, Nathan D., Daniel F. Mooney, and John P. Ritten. 2025. "Climate and Consolidation in the US Beef Cow Sector." *Journal of Agricultural and Resource Economics* 50(1): 97–118. https://doi.org/10.22004/ag.econ.344684.

Dennis, Elliott. 2021. “Forage Production, Beef Cows and Stocking Density and Their Implications for Partial Herd Liquidation Due to Drought.” UNL BeefWatch. Retrieved from: https://beef.unl.edu/beefwatch/2021/forage-production-beef-cows-and-stocking-density-and-their-implications-partial-herd.

Earth System Grid Federation. 2024. Earth System Grid Federation Data Portal. Accessed March 2025. https://aims2.llnl.gov/search

Granger, R. J. 1989. “An Examination of the Concept of Potential Evaporation.” *Journal of Hydrology* 111 (1–4): 9–19. <https://doi.org/10.1016/0022-1694(89)90248-5>.

Harmel, R.D., D.R. Smith, R.L. Haney, J. Angerer, N. Haile, L. Grote, S. Grote, K. Tiner, J. Goodwin, R. Teague, and J. Derner. 2021. “Transitioning from Conventional Continuous Grazing to Planned Rest-Rotation Grazing: A Beef Cattle Case Study from Central Texas.” *Journal of Soil and Water Conservation* 76 (6): 534–546. https://doi.org/10.2489/jswc.2021.00159.

Hart, Charles R., and Bruce B. Carpenter. “Stocking Rate and Grazing Management.” E-64. *Texas A&M AgriLife Extension*, 2001. Accessed June 9, 2025. https://llano.agrilife.org/files/2011/03/Stocking-Rate-and-Grazing-Management.pdf

Holechek, Jerry L. 1988. "An Approach for Setting the Stocking Rate." *Rangelands* 10 (1): 10–14. http://hdl.handle.net/10150/640265.

Huang, Na, Gretchen F. Sassenrath, and Xiaomao Lin. 2023. “Improving Resilience of Corn to Weather through Improved Fertilizer Efficiency.” *Kansas Agricultural Experiment Station Research Reports* 9 (2). https://doi.org/10.4148/2378-5977.8447.

Hrozenick, R. Aaron, and Gabriela Perez-Quesada. 2025. “Federal Drought Assistance and Adaptation Decisions in the U.S. Livestock Sector.” *Agricultural Economics*. https://doi.org/10.1111/agec.70042.

Iglesias, Virginia, William R. Travis, and Jennifer K. Balch. "Recent Droughts in the United States Are among the Fastest-Developing of the Last Seven Decades." *Weather and Climate Extremes* 37 (2022): 100491. <https://doi.org/10.1016/j.wace.2022.100491>.

Klemm, T., and D.D. Briske. "Retrospective Assessment of Beef Cow Numbers to Climate Variability throughout the U.S. Great Plains." *Rangeland Ecology & Management* 78, no. 1 (2019): 273–280. <https://doi.org/10.1016/j.rama.2019.07.004>.

Leeper, Ronald D., Rocky Bilotta, Bryan Petersen, Crystal J. Stiles, Richard Heim, Brian Fuchs, Olivier P. Prat, Michael Palecki, and Steve Ansari. "Characterizing U.S. Drought over the Past Twenty Years Using the U.S. Drought Monitor." *International Journal of Climatology* 42, no. 12 (2022): 6616–6630. <https://doi.org/10.1002/joc.7653>.

Luke, Jaime R., Andrew E. Anderson, and Glynn T. Tonsor. 2022. An Updated Evaluation of the U.S. Cattle Cycle. Kansas State University Department of Agricultural Economics Extension Publication. https://agmanager.info/livestock-meat/production-economics/evaluating-cattle-cycles-changes-over-time-and-implications

Luo, Qunying. 2011. “Temperature Thresholds and Crop Production: A Review.” *Climatic Change* 109 (3–4): 583–598. <https://doi.org/10.1007/s10584-011-0028-6>

Maples, Joshua G., Jayson L. Lusk, and Derrell S. Peel. 2016. *When Bigger Isn't Better: Steak Size and Consumer Preferences*. Selected Paper prepared for presentation at the 2016 Agricultural & Applied Economics Association Annual Meeting, Boston, Massachusetts, July 31–August 2.

Moore, K. M., T. N. Barry, P. N. Cameron, N. Lopez-Villalobos, and D. J. Cameron. 2003. “Willow (Salix sp.) as a Supplement for Grazing Cattle under Drought Conditions.” *Animal Feed Science and Technology* 104: 1–11. https://doi.org/10.1016/S0377-8401(02)00326-7.

Mu, Jianhong E., Bruce A. McCarl, and Anne M. Wein. "Adaptation to Climate Change: Changes in Farmland Use and Stocking Rate in the U.S." *Mitigation and Adaptation Strategies for Global Change* 18, no. 5 (2013): 713-730. <https://link.springer.com/content/pdf/10.1007/s11027-012-9384-4>.

National Drought Mitigation Center. n.d. “Grazing Pressure and Stocking Rate.” University of Nebraska. Accessed May 14, 2025. https://drought.unl.edu/ranchplan/BeforeDrought/GrazingStrategy/GrazingPressureandStockingRate.aspx.

Palmer, Wayne C., and A. Vaughn Havens. "A Graphical Technique for Determining Evapotranspiration by the Thornthwaite Method." *Monthly Weather Review* 86, no. 4 (1958): 123-128. <https://ion.sdsu.edu/onlinethornthwaitereference.pdf>.

Patalee, Buddhika M. A., and Glynn T. Tonsor. 2021a. “Impact of Weather on Cow-Calf Industry Locations and Production in the United States.” *Agricultural Systems* 193: 103212. https://doi.org/10.1016/j.agsy.2021.103212.

Patalee, Buddhika M. A., and Glynn T. Tonsor. 2021b. “Weather Effects on U.S. Cow-Calf Production: A Long-Term Panel Analysis.” *Agribusiness* 37 (4): 689–708. <https://doi.org/10.1002/agr.21697>.

Pendell, Dustin, Gary Brester, Ted Schroeder, Kevin Dhuyvetter, and Glynn Tonsor. "Animal Identification and Tracing in the United States." *American Journal of Agricultural Economics* 92, no. 4 (2010): 927–940.

PRISM Climate Group, Oregon State University. *PRISM Gridded Climate Data*. Accessed October 1, <http://prism.oregonstate.edu>.

Redfearn, Daren D., and Terrence G. Bidwell. "Stocking Rate: The Key to Successful Livestock Production." *OSU Extension*, Oklahoma State University. Accessed October 2, 2024. <https://extension.okstate.edu/fact-sheets/stocking-rate-the-key-to-successful-livestock-production.html>.

Ritten, J. P., Frasier, W. M., Bastian, C. T., & Gray, S. T. (2010). Optimal Rangeland Stocking Decisions Under Stochastic and Climate‐Impacted Weather. *American Journal of Agricultural Economics, 92*(4), 1242–1255.

Rodziewicz, David, Jacob Dice, and Cortney Cowley. "Drought and Cattle: Implications for Ranchers." *Federal Reserve Bank of Kansas City*, June 2, 2023. <https://doi.org/10.18651/RWP2023-06>.

Rowley, Cordon Michael. *The Impact of Drought on U.S. Hay Prices*. Master’s thesis, Kansas State University, 2023. Accessed June 8, 2025. <https://krex.k-state.edu/server/api/core/bitstreams/8b48ecdd-41c6-44fa-925a-c110e4159a09/content>

Smart, A. J., Derner, J. D., Hendrickson, J. R., Gillen, R. L., Dunn, B. H., Mousel, E. M., ... & Olsen, K. C. (2010). Effects of grazing pressure on efficiency of grazing on North American Great Plains rangelands. Rangeland Ecology & Management, 63(4), 397-406.

South Dakota State University. 2024. *Beef Grading.* Department of Animal Science. Accessed June 9, 2025. https://www.sdstate.edu/animal-science/judging/beef-grading

Spinoni, J., J. Vogt, and P. Barbosa. 2015. “European Degree-Day Climatologies and Trends for the Period 1951–2011.” *International Journal of Climatology* 35 (1): 25–36. https://doi.org/10.1002/joc.3959.

Srivastava, Aman, and Rajib Maity. “Unveiling an Environmental Drought Index and Its Applicability in the Perspective of Drought Recognition Amidst Climate Change.” *Journal of Hydrology* 627 (2023): 130462. <https://doi.org/10.1016/j.jhydrol.2023.130462>.

Teague, Richard, and Urs Kreuter. “Managing Grazing to Restore Soil Health, Ecosystem Function, and Ecosystem Services.” *Frontiers in Sustainable Food Systems* 4 (2020): Article 534187. https://doi.org/10.3389/fsufs.2020.534187.

University of Nebraska-Lincoln. 2024. Beef Production Calendar. Institute of Agriculture and Natural Resources. Accessed June 8, 2025. <https://beef.unl.edu/beef-production-calendar/>

U.S. Department of Agriculture. *Agricultural Marketing Service*. 2022a. Oklahoma National Stockyards Feeder Cattle Report – Oklahoma City, OK. <https://mymarketnews.ams.usda.gov/viewReport/1280>

U.S. Department of Agriculture. *Agricultural Marketing Service*. 2022b. Texas-Oklahoma-New Mexico Monthly Weighted Average Cattle Report – Negotiated Purchases. LM\_CT181. https://mymarketnews.ams.usda.gov/viewReport/2686

U.S. Department of Agriculture. *Census of Agriculture Historical Archive.* Accessed October 1, 2024.<https://agcensus.library.cornell.edu/#:~:text=Search%20Census%20Archive&text=The%20USDA%20Census%20of%20Agriculture,all%20historical%20agricultural%20census%20publications>.

U.S. Department of Agriculture. *Economic Research Service*. Farm Resource Regions. Agricultural Information Bulletin No. 760. Washington, DC: USDA ERS, September 2000. Accessed June 8, 2025. <https://ers.usda.gov/sites/default/files/_laserfiche/publications/42298/32489_aib-760_002.pdf?v=16960>

U.S. Department of Agriculture. *Economic Research Service*. 2022. Meat Price Spreads. Updated June 11, 2025. Accessed June 25, 2025. https://www.ers.usda.gov/data-products/meat-price-spreads/.

U.S. Department of Agriculture. *Economic Research Service*. 2025. Livestock and Meat Domestic Meat supply and disappearance tables, historical. Retrieved from: https://www.ers.usda.gov/data-products/livestock-and-meat-domestic-data

U.S. Department of Agriculture. *National Agricultural Statistics Service Quick Stats*. Accessed October 3, 2024. <https://quickstats.nass.usda.gov/>.

U.S. Department of Agriculture, *National Agricultural Statistics Service*. 2025. Livestock Slaughter. Accessed June 9, 2025. https://www.nass.usda.gov/Surveys/Guide\_to\_NASS\_Surveys/Livestock\_Slaughter.

Voth, Kathy. 2020. “How to Time Your Grazing to Improve Plant Yield and Quality.” *On Pasture*, May 4, 2020. <https://onpasture.com/2020/05/04/how-to-time-your-grazing-to-improve-plant-yield-and-quality/>.

Wooldridge, Jeffrey M. *Introductory Econometrics: A Modern Approach*. 5th ed. Mason, OH: South-Western Cengage Learning, 2012.

Zhou G., and Wang Q. “A new nonlinear method for calculating growing degree days.” *Sci Rep. 2018 Jul 5*;8(1):10149. doi: 10.1038/s41598-018-28392-z. PMID: 29977001; PMCID: PMC6033920.

## Appendix A. Robustness Checks

To assess the sensitivity of our model to key assumptions, we began by evaluating the definition of the grazing period. The baseline specification assumes a five-month grazing period and aggregates weather variables over the March-October season, as described in Equation (1). To test the robustness of our results, we re-estimated the model using alternative grazing durations of 4, 5, 6, 7, and 8 months. As expected, the magnitude of stocking rates increased proportionally with the number of grazing months assumed. However, the estimated coefficients remained stable across these specifications. This stability is attributable to the fact that weather variables were held constant over the March-October season. As such, varying the number of grazing months only altered the scale of the dependent variable without affecting the underlying causal relationships.

To conduct a more informative sensitivity analysis, we next vary the grazing season itself, allowing weather exposure to shift accordingly. We re-estimate the model using different alternative grazing seasons (see Table A1). For each specification, weather variables were re-aggregated to reflect the corresponding seasonal window, ensuring that climatic exposure aligns with the assumed grazing interval. This approach enables us to assess whether the estimated effects of drought, temperature stress, and hay availability are sensitive to the timing of seasonal exposure.

The estimated effects of current and lagged water deficit variable remain negative, statistically significant, and highly stable across all grazing season specifications. However, two notable patterns emerge. First, the smallest effect of current drought appears in the May-September window, suggesting producers may be less responsive to in-season drought during peak forage availability in that period. Second, the weakest lagged drought effect occurs in the June-October season, indicating that prior-year drought has less influence on late-season stocking decisions possibly due to earlier herd adjustments or reduced forage responsiveness later in the year.

The coefficients on GDD and EDD are statistically significant across all grazing seasons. The largest GDD coefficient is observed in the April-July window, suggesting that forage productivity is most responsive to thermal accumulation during this mid-spring to midsummer period. This likely reflects the critical importance of early-to-mid growing season temperatures in driving vegetative growth. The negative impact of EDD is most pronounced in March-July, indicating that forage systems are particularly vulnerable to extreme heat during this biologically sensitive window. Together, these findings reinforce the importance of targeting early-season weather exposure when assessing grazing capacity.

**Table A1. Robustness analysis results.**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Weather For: | | | | | | | | | | | | | | |
|  | 8 Months | 7 Months | | 6 months | | | 5 months | | | | 4 months | | | | |
|  | Mar-Oct | Mar-Sep | Apr-Oct | Mar-Aug | Apr-Sep | May-Oct | Mar-Jul | Apr-Aug | May-Sep | Jun-Oct | Mar-Jun | Apr-Jul | May-Aug | Jun-Sep | Jul-Oct |
|  | -0.0005\*\*\* | -0.0004\*\*\* | -0.0006\*\*\* | -0.0005\*\*\* | -0.0005\*\*\* | -0.0005\*\*\* | -0.0006\*\*\* | -0.0005\*\*\* | -0.0003\*\*\* | -0.0005\*\*\* | -0.0007\*\*\* | -0.0007\*\*\* | -0.0004\*\*\* | -0.0003\*\*\* | -0.0007\*\*\* |
|  | -0.0004\*\*\* | -0.0005\*\*\* | -0.0004\*\*\* | -0.0006\*\*\* | -0.0005\*\*\* | -0.0003\*\*\* | -0.0007\*\*\* | -0.0006\*\*\* | -0.0004\*\*\* | -0.0003\*\*\* | -0.0007\*\*\* | -0.0007\*\*\* | -0.0005\*\*\* | -0.0004\*\*\* | -0.0003\*\*\* |
|  | 0.0117\*\*\* | 0.0142\*\*\* | 0.0128\*\*\* | 0.0169\*\*\* | 0.0156\*\*\* | 0.0148\*\*\* | 0.0211\*\*\* | 0.0190\*\*\* | 0.0190\*\*\* | 0.0190\*\*\* | 0.0201\*\*\* | 0.0239\*\*\* | 0.0226\*\*\* | 0.0241\*\*\* | 0.0217\*\*\* |
|  | -0.0298\*\*\* | -0.0364\*\*\* | -0.0328\*\*\* | -0.0373\*\*\* | -0.0392\*\*\* | -0.0400\*\*\* | -0.0595\*\*\* | -0.0413\*\*\* | -0.0479\*\*\* | -0.0481\*\*\* | -0.1023\*\*\* | -0.0589\*\*\* | -0.0512\*\*\* | -0.0570\*\*\* | -0.0449\*\*\* |
|  | -0.0003\*\*\* | -0.0001\*\*\* | -0.0002\*\*\* | -0.0000\*\*\* | -0.0000\*\*\* | -0.0002\*\*\* | -0.0001\*\*\* | -0.0001\*\*\* | -0.0002\*\*\* | -0.0002\*\*\* | -0.0001\*\*\* | -0.0001\*\*\* | -0.0001\*\*\* | -0.0002\*\*\* | -0.0002\*\*\* |
|  | 0.65 | 0.65 | 0.65 | 0.65 | 0.64 | 0.64 | 0.65 | 0.64 | 0.64 | 0.64 | 0.64 | 0.64 | 0.64 | 0.64 | 0.64 |

Note: \*\*\* p < 0.01, \*\* p < 0.05, and \* p < 0.10. Main model is grayed.

1. The Census of Agriculture report is conducted every five years. [↑](#footnote-ref-1)
2. 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 1.2 AUs. If the pastureland is 100 acres, the stocking rate is 3.6 AUMs per acre. [↑](#footnote-ref-2)
3. The hay stocks data are derived from a national-level survey conducted by USDA NASS. County-level hay stock estimates are not consistently available across years. [↑](#footnote-ref-3)
4. 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-4)
5. The log transformation of the stocking rate is used for two reasons. First, interpreting coefficients from logged dependent variables in percentage terms provides intuitive and easily comparable insights into how explanatory variables influence stocking rates. Second, the log transformation mitigates potential heteroskedasticity by stabilizing the variance of residuals, especially beneficial when the dependent variable demonstrates a right-skewed distribution (Wooldridge 2012). Additionally, the log transformation helps normalize the distribution of stocking rates, further improving the robustness of econometric estimations. [↑](#footnote-ref-5)
6. To get total beef production we assume beef productivity of a calving rate of 85%, 3% calf mortality, and a 50:50 sex ratio with 20% heifer retention [↑](#footnote-ref-6)