**Core Ideas**

- Pasture and rangeland (grazing land) conditions tend to deteriorate from May through October in the U.S.
- Grazing land conditions are the least optimal on average across the southwestern domain of the U.S.
- Grazing land conditions have deteriorated in the West but improved in the East since 1995.

# United States Pasture and Rangeland Conditions: 1995-2022

Abbreviations: CCIndex, Crop Condition Index


## ABSTRACT

USDA National Agricultural Statistics Service pasture and rangeland condition data were used to establish a novel spatiotemporal climatology of condition ratings across the conterminous United States for the May–October grazing season over the 1995–2022 study period. On average, the coverage of grazing land that provides adequate or excess feed underwent a significant reduction during a typical season. Spatially, the southwestern United States exhibited the poorest grazing land conditions on average, with over twenty years below the national mean condition rating. At the national aggregated level, conditions degraded during the 28-year study period, and the most significant trends were observed for grazing lands considered to have poor or very poor condition coverage, which increased. Robustly increasing trends in poor and very poor condition coverage were most apparent across the western half of the United States, which is predominantly rangeland. Meanwhile, the eastern half of the United States, which is mostly pastureland, generally experienced condition improvements. Overall, continued regional climatic changes that may result in increasing temperatures, variable precipitation totals, and subsequent soil moisture declines leading to increased drought instances will continue to impose challenges

for grazing land managers. Grazing land condition declines can result in increased feed supply demand and reduced grazing capacity. Should these trends continue, there will be a growing need for flexible livestock, forage, and grazing management strategies in the coming decades to adapt to climate change-induced impacts on water-sensitive ecosystems.

## 1 INTRODUCTION

Pasture and rangeland systems across the United States serve as critical resources in various ecosystems that include habitat for livestock and wildlife, cropping systems, and energy production (White et al., 2000; Lund, 2007; Briske et al., 2015; McNeeley et al., 2017; Fernández-Giménez et al., 2019; Ojima et al., 2020). These lands encompass more than one-third of the U.S. land area, spanning over 2.1 million $km^2$ (USDA, 2019). They also comprise a similar global extent, serving as the backbone for operations associated with farming and ranching, conservation, and recreational enterprises, reflecting an active socio-ecological system (Havstad et al., 2007; Hruska et al., 2017; McCollum et al., 2017). Pastures are defined as land used for herbaceous forage crops that are highly managed and cultivated, while rangelands are an area of shrub and/or natural grass ecosystems primarily used for extensive livestock production (FAO, 2023). As the demand for livestock production increases alongside population growth, there will be increased stress on pastures and rangelands (grazing lands) from both land use intensification and climate change (Stanimirova et al., 2019). There is general agreement that climatic conditions have resulted in changes to biodiversity, ecosystem processes, and the overall quality and productivity of grasslands across the United States (Polley et al., 2013; Ojima et al., 2020). Therefore, decreasing environmental impacts on grazing lands while sustaining the demand for meat and dairy products will depend on sensitivity to climate and adaptive livestock management (Sauchyn & Kulshreshtha, 2008; Bestelmeyer & Briske, 2012; McCollum et al., 2017; Fernández-Giménez et al., 2019; Hanberry et al., 2019; Stanimirova et al., 2019).

The profound effects of climate change on grazing lands and subsequent livestock operations will vary by region, vegetation community, and livestock type (Briske et al., 2015; Joyce et al., 2013; McCollum et al., 2017; Bolster et al., 2023). Many aspects of the grazing system ecology (e.g., forage—biomass that is potential food for livestock) are determined by the spatiotemporal distribution of precipitation and the resulting impacts on soil water availability (Campbell et al., 1997; Knapp et al., 2001; Morgan, 2005). Therefore, the onset of drought and extreme rainfall events, in addition to warmer summers, land fragmentation, and invasive non-native species, will continue to have negative impacts on grazing systems across the United States (Polley et al., 2013; Archer et al., 2017; Bestelmeyer et al., 2018). While these lands encompass a large share of the agricultural landscape in the United States, their productivity and resilience to climate change have received comparatively less attention than croplands (Ramankutty et al., 2002; Foley et al., 2011; Izaurralde et al., 2011). Due to the significance grazing lands have in ecological systems and on local and global economies (ERS, 2023), the insufficient comprehension of the vulnerabilities to climate is a key knowledge gap in the field (Stanimirova et al., 2019). The condition, or quality, and overall success of grazing operations are based on the seasonal distribution and quantity of forage, interannual reliability of forage production, and forage nutritional value (e.g., Wu & Rykiel, 1986; Sollenberger & Vanzant, 2011). Hence, there is an inherent need to study and actively monitor both pastures and rangelands continuously throughout the year, along with furthering the understanding of processes and thresholds that lead to deteriorating conditions (Keesstra et al., 2016). There is also a literature gap regarding the generalized base state of pasture and rangeland conditions and how these conditions have trended over time under the influence of climate change. Observed gradual changes and future changes in climate can induce sudden shifts in vegetation quality and quantity to less-than-optimal conditions where recovery may be irreversible (Briske et al., 2005, 2006; Bestelmeyer et al., 2009). Threshold statistics—or, in the case of this research, climatologies—play a vital role in assessing the resilience of ecosystems to climate change and provide insights into the necessity and timing of potential management intervention (Standish et al., 2014). Therefore, a baseline grazing land condition climatology and comprehensive analysis of condition trends across the United States are essential in furthering the understanding for land managers, researchers, and other stakeholders with novel information to assist with in-season production and future decisions regarding sustainability.

Established qualitative and quantitative methods to monitor pasture and rangeland quality at relevant scales do exist (e.g., Pyke et al., 2002; Mitchell, 2010; McCollum et al., 2017). However, to date, none have explored the comprehensive USDA National Agricultural Statistics Service (NASS) general crop condition dataset, which consists of subjective weekly pasture and rangeland condition ratings by U.S. state. USDA NASS general crop condition data have been used more recently in literature to quantify agricultural market reactions to crop condition changes (Lehecka, 2014; Bain & Fortenbery, 2016), seasonal tendencies and condition spatiotemporal trends (Irwin & Good, 2017a, 2017b; Irwin & Hubbs, 2018; Bundy & Gensini, 2022; Bundy et al., 2024), and how crop conditions react to extreme weather perils (Bundy et al., 2023). For the first time, this research establishes a state and national baseline grazing land climatology by 1) quantifying pasture and rangeland condition tendencies for the May–October grazing season, 2) quantifying seasonal averages and variability for each state, and 3) quantifying spatiotemporal trends in conditions throughout the conterminous United States for the 1995–2022 period (28 years) using USDA NASS condition data. Pastures and rangelands are undeniably complex and require adaptive management approaches (Bestelmeyer & Briske, 2012; McCollum et al., 2017; McNeeley et al., 2017; Fernández-Giménez et al., 2019), which include, but are not limited to, grazing with multiple paddocks, frequent livestock rotation, longer rest periods for forage recovery, optimizing herd sizes, and strategic water distribution. Thus, these new findings will appeal to land managers and policymakers by providing novel material to help foster informed decision-making on a weekly basis, prompt adaptation and management strategies, promote investigating the multitude of available insurance programs, and help to address environmental changes and land use demands to ensure a sustainable future.

## 2 MATERIALS AND METHODS

### 2.1 Data background

The USDA NASS Crop Progress and Condition (CPC) report provides subjective data collected by extension agents and Farm Service Agency staff, who are asked on a weekly basis (week ending on Sunday) from April through November to report estimates of crop progress and conditions based on USDA standard definitions (USDA, 2019). In addition to crops, as noted in Section 1, the survey covers pastures and rangelands across the conterminous United States (**Figure 1**). Surveys are quality-controlled by NASS by performing careful comparisons with previous weeks, historical averages, and data from other counties. NASS then takes these raw data and summarizes from county to state level and are weighted using pasture acreage and/or livestock inventories from the most recent Census of Agriculture (USDA, 2023b).

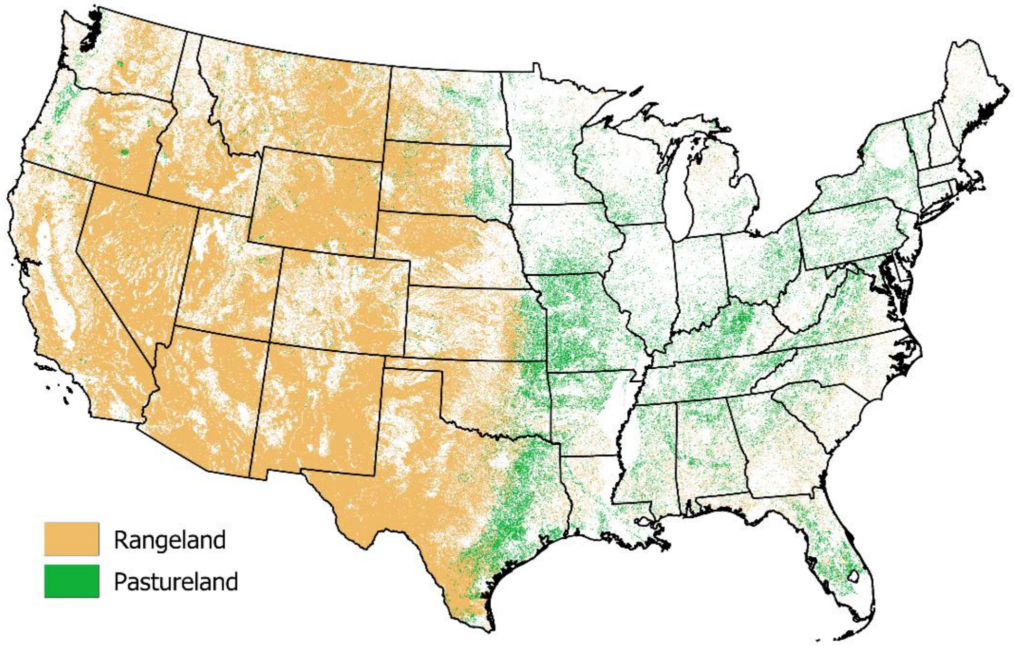


**Figure 1**. Land cover of pastures and rangelands at 30-meter spatial resolution for the conterminous United States based on the National Land Cover Database 2021 (USGS, 2023).

Confidentiality is conserved for the producers whose operations cover much of the production in a county (Rosales, 2021). Thereafter, state-level estimates are quality-controlled by comparing with surrounding states and historical averages, and then computed at the national level by weighting each state by its respective acreage and/or livestock inventories.

For the conditions portion of the CPC report, reporters are asked to estimate the percent of their operation in excellent, good, fair, poor, or very poor condition. While the dataset does consist of both pastures and rangelands, the USDA QuickStats database uses the term "pastureland" to simplify. General pastureland condition categories defined by the USDA are as follows (USDA, 2016):

- *Excellent*: Pastures are supplying feed in excess of what is normally expected at the current time of year.
- *Good*: Pastures are providing adequate feed supplies for the current time of year.
- *Fair*: Pastures are providing generally adequate feed but are still less than normal for the time of year.
- *Poor*: Pastures are providing only marginal feed for the current time of year. Some supplemental feeding is required to maintain livestock conditions.
- *Very Poor*: Pastures provide very little or no feed considering the time of year. Supplemental feeding is required to maintain livestock conditions.

The USDA-defined Crop Condition Index (CCIndex) was calculated for each report through the following (Rosales, 2021):

$$CCIndex = (5 * Excellent + 4 * Good + 3 * Fair + 2 * Poor + Very\ Poor) / 100 \quad (1)$$

This weighted index provides a rating summarizing the current state of weekly conditions for the five categories. The CCIndex ranges from 1 to 5, with an index rating of 5 corresponding to 100% of the surveyed crop being reported in excellent condition, and an index rating of 1 corresponding to 100% of the crop being reported in very poor condition (Rosales, 2021). While there are other ways to summarize each condition category (e.g., Irwin & Good, 2017a, 2017b; Irwin & Hubbs, 2018; Bundy & Gensini, 2022), the USDA-defined index was used for consistency with Bundy et al. (2024), where ten major field crop conditions were examined using the USDA NASS crop condition dataset. Therefore, the results of this analysis (pasture and rangeland conditions) can effectively be compared with CCIndex results for crop conditions from Bundy et al. (2024). Results for each condition category (excellent, good, fair, poor, and very poor) along with the CCIndex were also examined and provided as a supplemental file.

The USDA NASS condition dataset does have its limitations, one of which is the state-level spatial resolution given that multiple states have both pastures and rangelands (e.g., the Great Plains region). The data are subjective estimates of conditions, which means there is the possibility for human error and biased interpretation, leading to the potential for spatial and temporal biases. While spatiotemporal trends in USDA NASS condition data may significantly be influenced by climate change, it is important to recognize that changes over time and variations between states may also be related to possible changes in the methodology of estimating conditions (Irwin & Good, 2017b). It is also speculated that changes in the make-up of crop observers through time may also contribute to any observed changes in conditions (Irwin & Good, 2017b).

Regardless of these limitations, previous literature has noted that, despite the potential for spatial and temporal biases, the CPC report containing these condition data has the capability to capture the complexities of assessing near real-time conditions better than any other product (Begueria & Maneta, 2020). This is due to the condition rating data encapsulating the expert knowledge from the thousands of extension agents and Farm Service Agency staff, creating an elaborate network of “people as sensors” that provide ground truth for real-time crop and grazing conditions (Begueria & Maneta, 2020). Additionally, strong correlations have been observed between state condition data and climate variables (temperatures, precipitation, soil moisture), validating the use of these data in research and in practice (Bundy & Gensini, 2022; Bundy et al., 2024). Overall, this network of people who curate the USDA NASS condition data has proven valuable in previous literature that have used the data to accurately forecast yield with statistical significance (Irwin & Good, 2017a, 2017b; Irwin & Hubbs, 2018; Bundy et al., 2022, Bundy et al., 2024), forecast market movements (Lehecka, 2014; Bain & Fortenbery, 2016), and understand condition reactions to weather and climate perils (Bundy et al., 2023).

## 2.2 Data collection

Weekly pasture and rangeland, henceforth referred to as “grazing land,” condition data were collected from USDA NASS for the 1995–2022 period from May through October at state and national-aggregated levels (USDA, 2023b). April and November were discarded from the analysis due to incomplete and inconsistent data availability. From calendar weeks 18 through 43 (26 weeks), each state contained a full 28 years of condition data during each week. While some weeks overlap at the end and beginning of a month (and can vary annually), weeks were assembled into the respective months as follows: weeks 18–21, May; weeks 22–25, June; weeks 26–30, July; weeks 31–34, August; weeks 35–39, September; and weeks 40–43, October. Since the study period does not cover the entire year, the verbiage “warm season” is used herein when discussing the entirety of the May–October period.

## 2.3 Methods

Statistical methods of this research follow Bundy et al. (2024). A spatiotemporal grazing land condition analysis was generated using weekly condition category and CCIndex ratings, monthly-averaged ratings, and warm-season-averaged ratings from national and state perspectives. State and national averages were generated using the weekly condition data by calculating the monthly mean for each year using the following:

$$\overline{CCIndex}_{m,y} = \frac{1}{n_{m,y}} \sum_{w=1}^{n_{m,y}} CCIndex_w \qquad (2)$$

where m is the specific month and y is the year of interest, n is the total number of weeks within the month and year, and $CCIndex_w$ is the CCIndex rating within that week. Then, to compute the monthly mean CCIndex ratings over the 1995–2022 period, the means for a specific month were summed across all years and divided by the total number of years (28 years):

$$\overline{CCIndex}_m = \frac{1}{28}\sum_{y=1995}^{2022} CCIndex_{m,y} \quad (3)$$

Equations 2 and 3 were both used to calculate the monthly state averages for each of the categorical conditions (excellent, good, fair, poor, and very poor). To calculate the warm-season mean CCIndex ratings, the same approach was used when calculating the monthly mean, as the CCIndex rating was summed for each week within a specific year and divided by the total number of weeks (26 weeks). Then, these annual values were summed and divided by the total number of years. Along with condition averages, standard deviations were computed to assess the variability of conditions from warm season to warm season. Monthly standard deviations for each year were computed using the following with the same variables as defined in Equations 2 and 3:

$$\sigma_{m,y} = \frac{1}{n_{m,y}}\sum_{w=1}^{n_{m,y}} (CCIndex_{w,m,y} - \overline{CCIndex}_{m,y}) \quad (4)$$

To get the monthly CCIndex standard deviation over the 1995–2022 period, the monthly standard deviations for a specific month were summed across all years and divided by the total number of years (28 years):

$$\bar{\sigma}_m = \frac{1}{28}\sum_{y=1995}^{2022} \sigma_{m,y} \quad (5)$$

Using the generated weekly, monthly, and warm-season averages, trends were calculated at state and national levels using Theil-Sen's slope due to its insensitivity to outliers and robust computation when compared to other linear regression models (Wilcox, 2010). Statistical significance of Theil-Sen's slope was assessed using Kendall's τ statistic at a 95% significance level ($p$-value <0.05).

# 3 RESULTS

## 3.1 Condition climatology

### 3.1.1 National level

During the warm season over the 1995–2022 study period, on average, 45% of U.S. grazing land acreage was in favorable condition where these lands provided adequate or an excess of feed (excellent or good condition), whereas the remaining 55% of acreage was in a less-than-ideal condition that required some extent of supplemental feeding to maintain livestock (fair, poor, or very poor; **Figure 2**). Grazing land conditions at the national-aggregated level from weeks 18–43 deteriorated on average, with a total CCIndex change of -0.35 (**Figure 2a**). This deterioration in conditions corresponded to a 14% total decline in excellent or good conditions, consequently resulting in a 1% increase in fair conditions and a 13% increase in poor or very poor conditions (**Figure 2b–d**). While early-season (May through mid-June) and late-season (September through October) conditions tended to remain steady or even slightly improve, robust grazing land condition changes occurred from mid-June through August. Moreover, coverage of excellent and good-conditioned grazing lands combined for a 1–2% decline per week on average, whereas poor and very poor conditions combined for an increase in coverage of 2–3% per week during the mid-June through August epoch. By the end of the season, poor or very poor conditions covered nearly one-third of the U.S. grazing land from the one-fifth coverage at week 18. Additionally, deterioration in grazing land conditions throughout the season resulted in only a 4–6% difference between excellent/good and poor/very poor conditions in September and October as compared to the 30–36% difference in May and June.

In addition to assessing weekly averages, examining historical variability in grazing land condition coverage is essential to further the understanding when conditions are most, or least, sensitive to seasonal fluctuations. Overall, conditions were most variable during July and August, when conditions declined the most (**Figure 2**). Standard deviations for excellent/good conditions combined during weeks 26–35 ranged 11−14% while poor/very poor conditions ranged 10−13%, both of which were seasonal highs in variability. High variability can be characterized by years during the study period where conditions deviated substantially from average. For example, during July and August of 2012, 80% of U.S. land area and nearly 75% of livestock experienced some degree of drought condition (UNL, 2023). Further, seventeen of the twenty worst (lowest) weekly national grazing land conditions occurred in 2012. Across these seventeen weeks, only 19% of grazing land acreage was in excellent or good condition on average (25% below normal), while 57% of acreage was in poor or very poor condition (31% above normal).

Despite 2012 having some of the lowest weekly grazing land conditions on record, 2022 exhibited the worst warm-seasonal grazing land conditions across the United States in the 1995–2022 study period (2012 was the second worst, 2021 was the third worst). Meanwhile, eight of the ten best (highest) weekly grazing land conditions were in 1995, where excellent/good combined condition coverage averaged 73% (poor/very poor coverage only at 6%), which was 29% above the national warm-season excellent/good average. Thus, both extremes have occurred historically, and intraseasonal grazing land variability was found to be higher than several field crops, including barley, corn, cotton, oats, peanuts, rice, soybeans, and winter wheat at the seasonal and national level (Bundy et al., 2024).

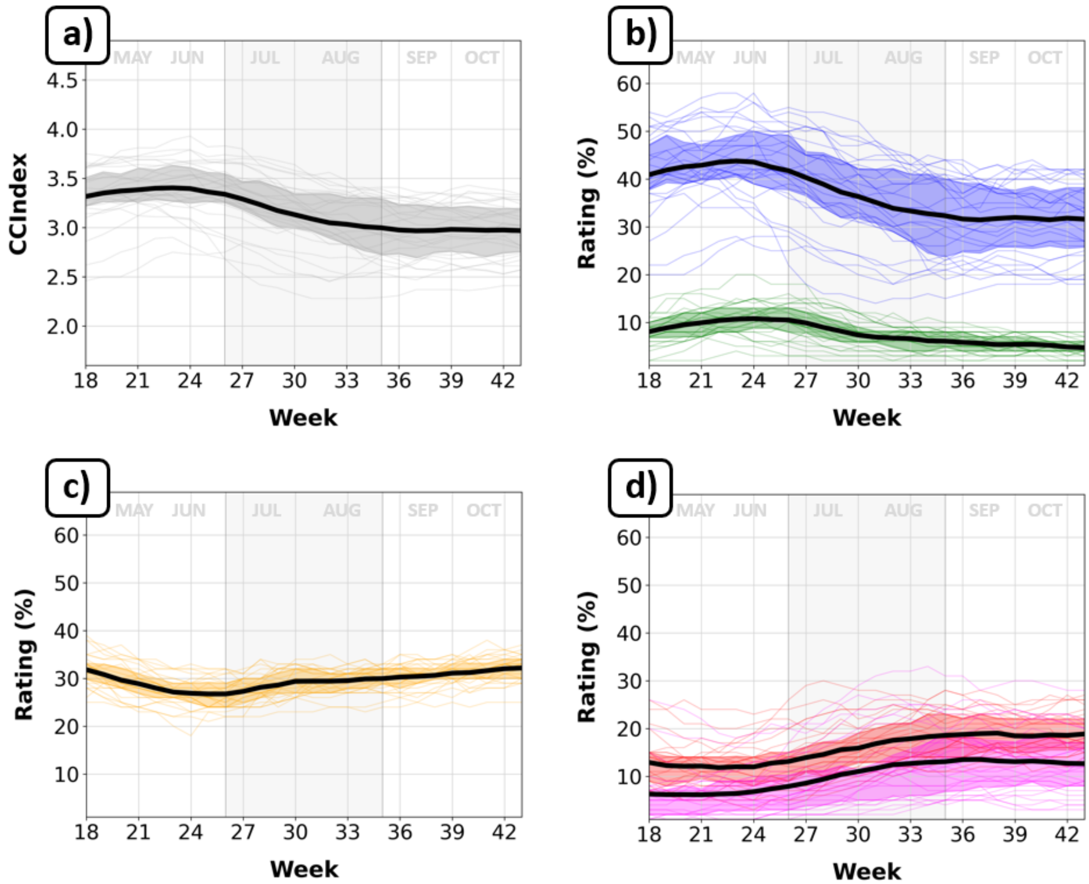


**Figure 2.** Weekly U.S. pasture and rangeland (grazing land) average ratings (black lines) by a) CCIndex rating (gray); b) excellent (green) and good condition (blue); c) fair condition (yellow); and d) poor (red) and very poor condition (magenta). Interquartile ranges are represented by the shading of the condition's respective color, and each of the week's condition rating values are plotted for each year in the study period (1995–2022) by the condition's respective color. Gray shaded area represents weeks within July and August, while the first white area is May and June, and the second white area is September and October.

### 3.1.2 State level

At the monthly aggregated interval, grazing land condition averages exhibited a correlation coefficient of -0.59 with monthly standard deviations. Essentially, higher monthly averages in the CCIndex, or better overall grazing land conditions, generally reflect lower intermonthly variability (**Figures 3 and 4**). Specific state averages and standard deviations by month and condition category (excellent, good, fair, poor, very poor) were examined but will not be discussed here for brevity (**Supplemental Tables S1 and S2**). Grazing land conditions during May and June were most optimal across the eastern North-Central and Northeast U.S. regions, with CCIndex ratings exceeding 3.60 (**Figure 3a, 3b**). Only seven states recorded a CCIndex rating lower than the seasonal national average of 3.29 in May or June—New Mexico, Arizona, Texas, Florida, Colorado, Montana, California, and Georgia. However, Florida, New Mexico, and Arizona were the only three states to improve in grazing land condition averages as the season progressed, with net increases in CCIndex ratings of >0.20 (**Figure 3c–f**). Therefore, all other states experienced a deterioration of grazing land condition averages throughout the warm season, with the most substantial declines observed in California and Oregon (CCIndex rating changes of -1.16 and -0.88, respectively), across the Midwest in Indiana and Illinois (CCIndex rating changes of -0.81 and -0.76, respectively), and, more broadly, across much of the northern half of the United States (~north of 35° N latitude).

In addition to experiencing some of the lowest monthly grazing land conditions, the southwestern U.S. region also experienced higher-than-normal variability over the 1995–2022 study period during all warm season months (**Figure 4**). States within the southwestern U.S. region and adjacent areas of the West—California, Arizona, Nevada, New Mexico, Colorado, Texas, and Montana—were the only states to obtain a standard deviation above the national seasonal CCIndex standard deviation of 0.49 in all six months. Meanwhile, variability across the eastern North-Central region as well as the Mississippi Delta and Northeast U.S. regions was on the lower side (<0.49) through May and June. For the remainder of the warm season, variability was higher across these regions, contributing to the general deterioration of grazing land conditions through the warm season in the eastern half of the United States. The only states to decrease in grazing land condition variability from May through October were Florida, California, and Arizona, with CCIndex standard deviation changes of <-0.10.

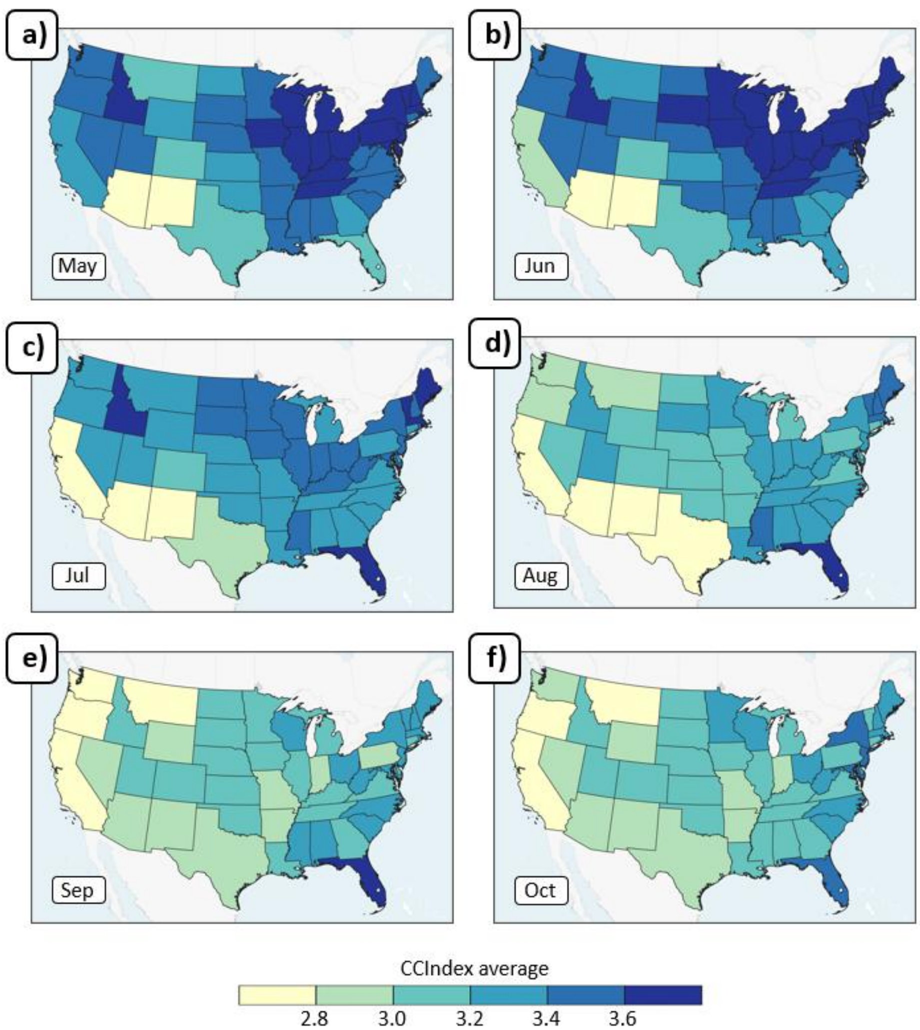


**Figure 3**. Monthly averages (May–October; 1995–2022) of pasture and rangeland CCIndex ratings by U.S. state.

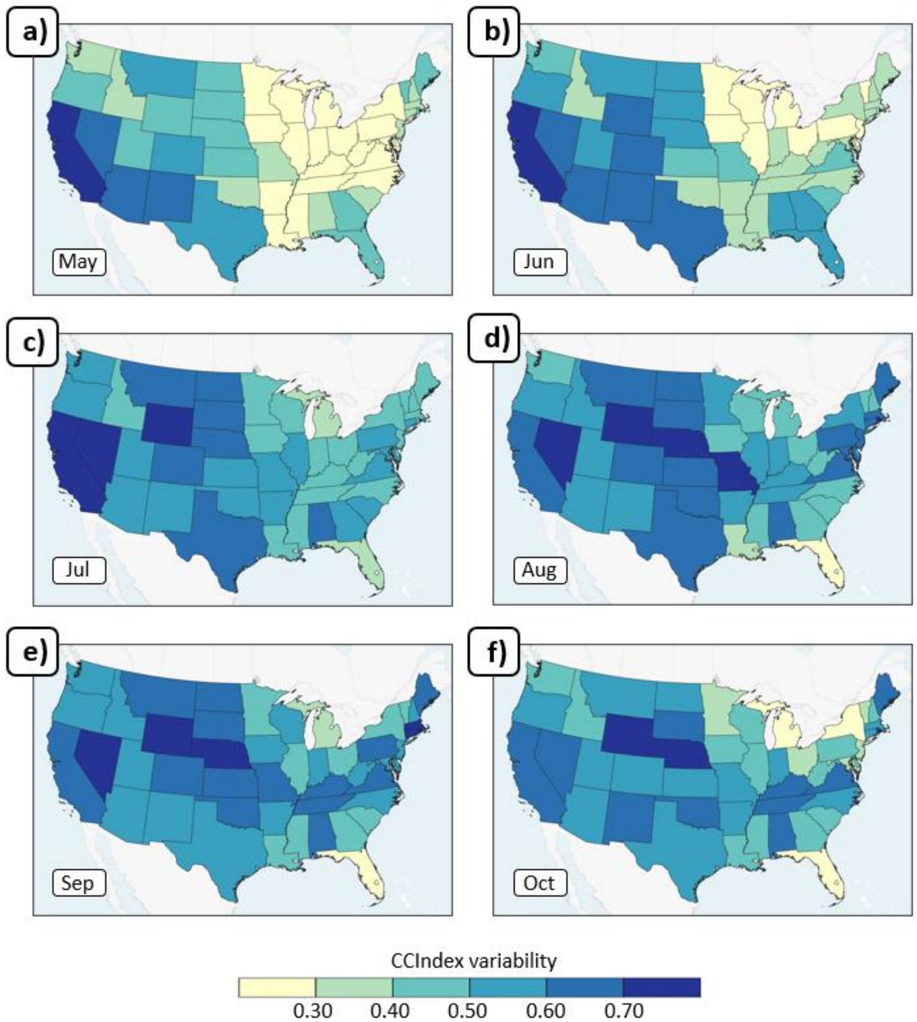


**Figure 4.** Monthly variability from warm season to warm season (May–October; 1995–2022) measured by standard deviation of pasture and rangeland CCIndex ratings by U.S. state.

Overall, there were notable differences in grazing land condition averages when comparing the eastern and western halves of the United States. All warm-season metrics using the CCIndex, including rating averages (**Figure 5a**), number of years below the national warm season average (**Figure 5b**), departure from the national seasonal average (**Figure 5c**), and standardized anomalies from the national average (**Figure 5d**), suggest conditions across the southwestern United States and, more broadly, the western United States were suboptimal when compared to the rest of the country. California, Arizona, and New Mexico were three states of note where grazing land CCIndex ratings averaged below 2.80 on a warm-seasonal basis (<-0.35 below normal; <-2.0 standard deviations below normal), which was the result of 24 of the 28 years in the historical record registering below the national average.

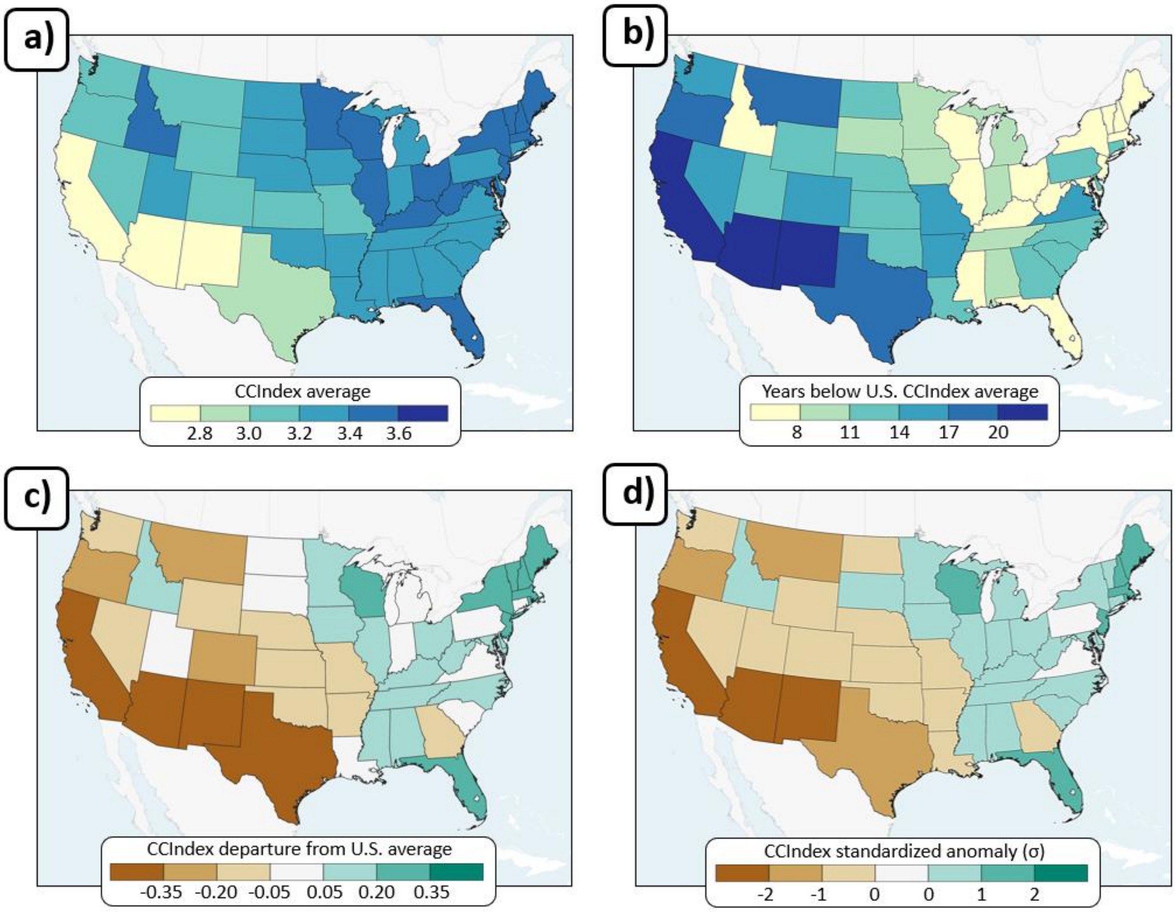


**Figure 5.** Warm season summaries by U.S. state of pasture and rangeland a) CCIndex rating averages; b) number of warm seasons below the U.S. CCIndex rating average; c) CCIndex rating departures from the U.S. average; and d) standardized anomalies from the U.S. average (1995–2022).

California, Arizona, and New Mexico were the only three states to have a higher percentage of grazing land in poor or very poor condition than in excellent or good condition for at least four of the six warm-season months (**Supplemental Table S1**). Arizona and New Mexico were also the only states to have higher variability in poor or very poor condition than excellent or good condition in each warm-season month (**Supplemental Table S2**).

## 3.2 Condition trends

### 3.2.1 National level

Over the 28-year study period, at the national warm-seasonal average level, grazing land conditions have deteriorated statistically insignificantly, with a CCIndex rating change of -0.007 $\cdot$ $yr^{-1}$ (**Figure 6a**). Excellent and good condition coverage has subtly declined nationally by 0.06% $\cdot$ $yr^{-1}$ and 0.17% $\cdot$ $yr^{-1}$, respectively, which was not statistically significant to the 95% significance level (**Figure 6b**). These trends from 1995 through 2022 equated to a 2% decrease in excellent condition coverage and a 5% decrease in good condition coverage for grazing lands across the United States, consequently requiring more supplemental feed supply to maintain livestock conditions. For fair conditions, which are considered a less-than-normal condition for the time of year, coverage trends were the lowest of all conditions at -0.03% $\cdot$ $yr^{-1}$, equating to only a 1% change over the 28-year period (**Figure 6c**). Poor condition coverage increased by 0.05% $\cdot$ $yr^{-1}$,

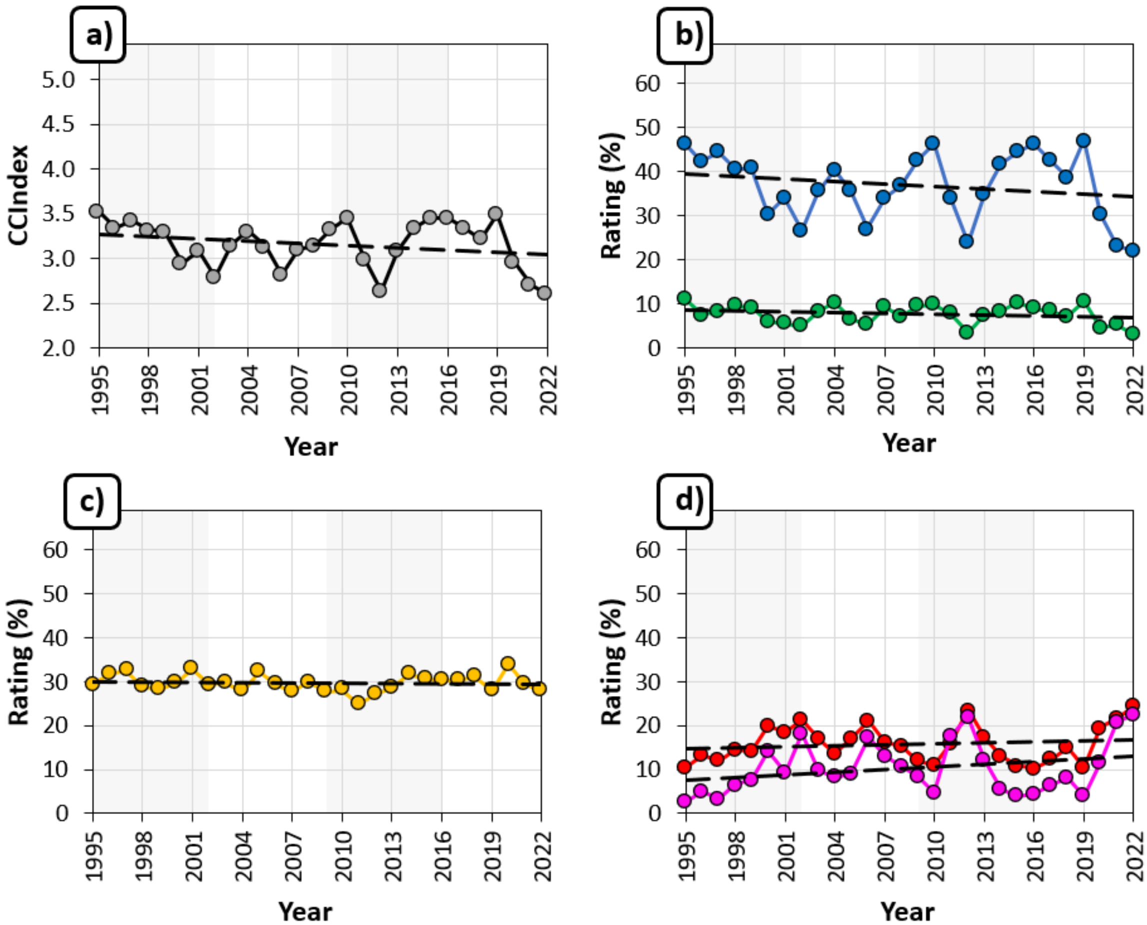


**Figure 6.** Warm-seasonal average U.S. pasture and rangeland ratings by a) CCIndex rating (gray); b) excellent (green) and good condition (blue); c) fair condition (yellow); and d) poor (red) and very poor condition (magenta). The black dashed line represents the Theil-Sen slope, and the gray sections separate four equal epochs within the study period (1995–2022).

which represented a 1% increase over time. While not statistically significant, the most robust trend was in the increase in very poor conditions, with a seasonal increase of 0.21% · $yr^{-1}$ equating to a 6% increase in coverage (**Figure 6d**). Therefore, grazing lands that were considered in good, excellent, or fair condition were more often being downgraded to poor or very poor condition over time.

Much of these overall negative trends for grazing lands have come from conditions in recent times. 2022 was the only year in the USDA NASS historical record of grazing land conditions where there was a higher coverage of poor conditions than excellent and good coverage, and a higher coverage of very poor conditions than excellent and good coverage. 2021 was also suboptimal, as poor or very poor condition coverage was 14% higher (42% of acreage) than the combined excellent or good condition coverage (28% of acreage). Conversely, national grazing land conditions have never been more optimal than 1995 (warm-season CCIndex rating of 3.52), which is the beginning of the historical record, as the combined excellent/good conditions covered 57% of national acreage and poor/very poor conditions represented a historically low 13% of acreage.

Also of importance, rapid fluctuations in grazing land conditions in recent times contribute to the trend in interseasonal variability. When separating the 28-year study period into four equal epochs (1995–2001; 2002–2008; 2009–2015; 2016–2022), standard deviations have increased over time for each condition category along with the CCIndex. For the CCIndex at the warm-season and national level, the standard deviation in the first period increased from 0.19 to 0.36 by the final 7-year period. Variability within the 7-year periods was comparable between excellent/good and poor/very poor conditions, as the standard deviation for these condition combinations went from 7% in 1995–2001 to nearly doubling at 13% in 2016–2022. The increasing variability and statistically insignificant national condition trends can be attributed to the observed 3–5-year cyclic patterns in seasonal-averaged grazing land conditions (**Figure 6**). Though, a thorough investigation of the causes of the cyclic nature of national-level grazing lands and potentially state-level conditions goes beyond the scope of this research.

At the national aggregated level, grazing land condition coverage trends were also investigated at the highest temporal interval (weekly) between May and October (**Figure 7**). Overall, deteriorating grazing land trends have occurred within a majority of warm-season weeks, as there were only two weeks that did not display a decreasing CCIndex trend—weeks 36 and 37 in mid-September. While 24 of the 26 examined weeks underwent a deteriorating trend in grazing land conditions, only one of these weeks was statistically significant at the 95% significance level (week 25 in late June). This coincides with when the most robust negative trends occurred, which, more broadly, was between week 23 and week 30, encompassing late June and all of July. During the late June through July period, excellent condition coverage declined by as much as -0.17% · yr$^{-1}$, while good condition coverage decreased by as much as -0.30% · yr$^{-1}$. These trends corresponded to a 5% and 8% total decrease, respectively, over the 28-year study period within the weeks in late June and July.

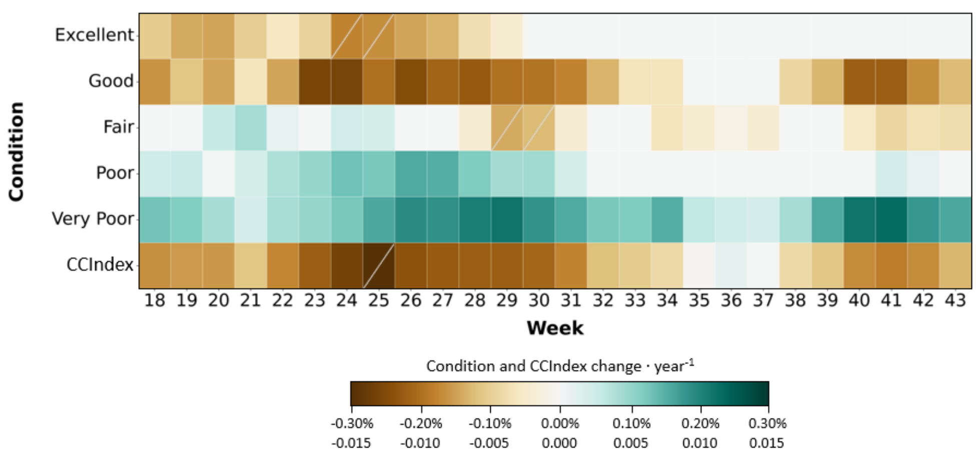


**Figure 7.** Theil-Sen slope results of interweekly trends in U.S. pastureland condition ratings (1995–2022). Slope units for condition categories are percent increases or decreases in condition coverage per year (first row under color bar), and slope units for CCIndex ratings are increases or decreases in CCIndex per year (second row). Hatching signifies statistical significance at the 95% confidence level using Kendall's Tau statistic.

Furthermore, coverage in poor and very poor conditions during the late June through July window increased by as much as 0.24% · $yr^{-1}$, which equated to a 7% increase in coverage over the 28-year study period within these weeks. Prior to this period, trends in optimal grazing land conditions in May were also in a declining mode, with excellent and good condition coverage decreases ranging from -0.12% · $yr^{-1}$ to -0.18% · $yr^{-1}$. While the late June through July period displayed the most robust trends for grazing land conditions across the United States, weeks 35 through 37 (early September) displayed only subtle changes or no trends at all before switching back to the declining mode for the remainder of the warm season. Though, these trends represent the United States, and thus, statewide trends need to also be assessed to further understand the changing pasture and rangeland condition landscape.

### 3.2.2 State level

Using the CCIndex, distinct spatiotemporal trends in grazing land conditions were observed across the United States at the intermonthly interval (**Figure 8**). Specific condition category trends by state and month can be examined in **Supplemental Table S3**. In each month, much of the western United States underwent a decline in grazing land conditions over the 1995–2022 period; Nevada and Oregon were the only two U.S. states to display a statistically significant trend in at least five of the six warm season months. Both states experienced a decreasing CCIndex trend lower than -0.03 · $yr^{-1}$, and both states were in the top-five for declining grazing land condition trends over the 28-year study period. Washington was the only state in the western United States to have experienced an improvement, albeit statistically insignificant, in grazing land conditions over the study period during at least one of the months (July). More broadly, at least 30 of the 48 states (63%) displayed a decreasing trend in grazing land conditions in May, June, and July (**Figure 8a–c**), while less than half the states underwent a decreasing trend in August, September, and

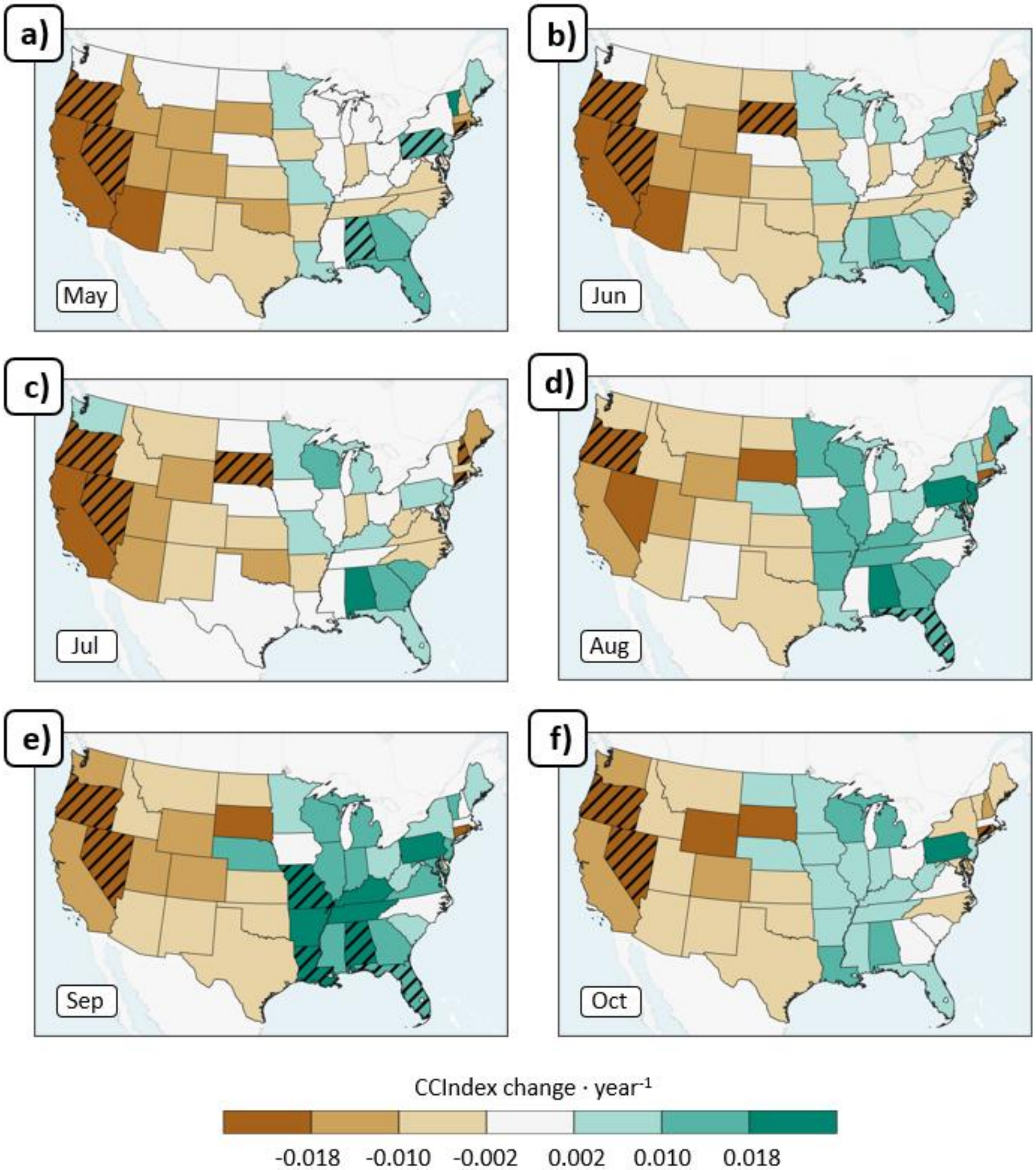


**Figure 8.** Theil-Sen slope results for intermonthly trends (May–Oct) in pasture and rangeland CCIndex ratings by U.S. state (1995–2022). Slope units are in percent increase or decrease in CCIndex per year. Hatching signifies statistical significance at the 95% confidence level using Kendall’s Tau statistic.

October (**Figure 8d–f**). Meanwhile, in general, the eastern half of the United States experienced an improvement in grazing land conditions, primarily in August, September, and October. The most robust improvements occurred in the Mississippi Delta and adjacent southeastern U.S. regions, where six states in these regions during September displayed statistically significant CCIndex rating trends upwards of $0.03 \cdot yr^{-1}$. These improving grazing land conditions collocate with where field crop conditions have significantly improved through the USDA NASS crop condition historical record (Bundy et al., 2024).

When aggregated to the warm-seasonal level and examined by condition category, the eastern/western United States divide in condition trends was also apparent (**Figures 9 and 10**), which follows suite with the divide between rangelands (predominantly in the western United States) and pastures (predominantly in the eastern United States). That is, excellent and good conditions have decreased most substantially in the western United States, with declines in Nevada and Oregon for good condition coverage worse than $-1.0\% \cdot yr^{-1}$—the only two states to have any trend be worse than $-1.0\% \cdot yr^{-1}$. Perhaps the most notable of these trends were the widespread statistically significant increases in very poor conditions in the western half of the United States (**Figure 9e**). Very poor condition coverage trends had the greatest number of states (six total) with a statistically significant increasing trend. Arizona, California, and Oregon underwent the most robust increases in very poor condition coverage, with increases greater than $0.45\% \cdot yr^{-1}$, equating to almost a 13% increase in grazing land coverage that provided little or no feed within each of these states. From a categorical coverage change standpoint, the largest changes were good conditional coverage being downgraded in the western United States to poor or very poor condition, while poor or very poor conditions improved in the eastern United States to at least a good condition (**Figure 10**). Meanwhile, trends in the central United States were mixed, with a subtle increase in good condition coverage but also an increase in very poor condition coverage.

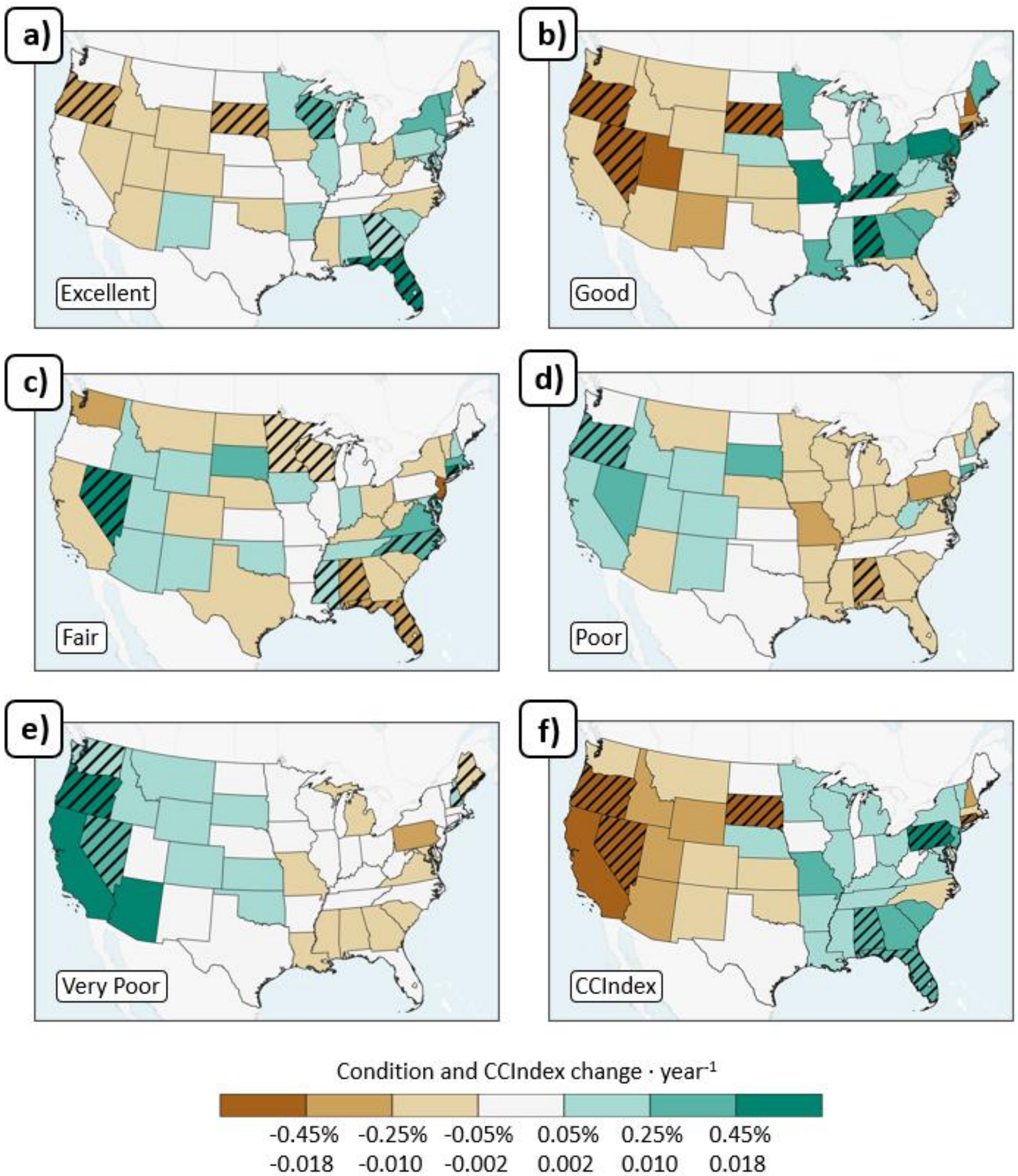


**Figure 9.** Theil-Sen slope results for interwarm season trends (1995–2022) in pasture and rangeland condition ratings by U.S. state. Slope units are same as in Figure 7.

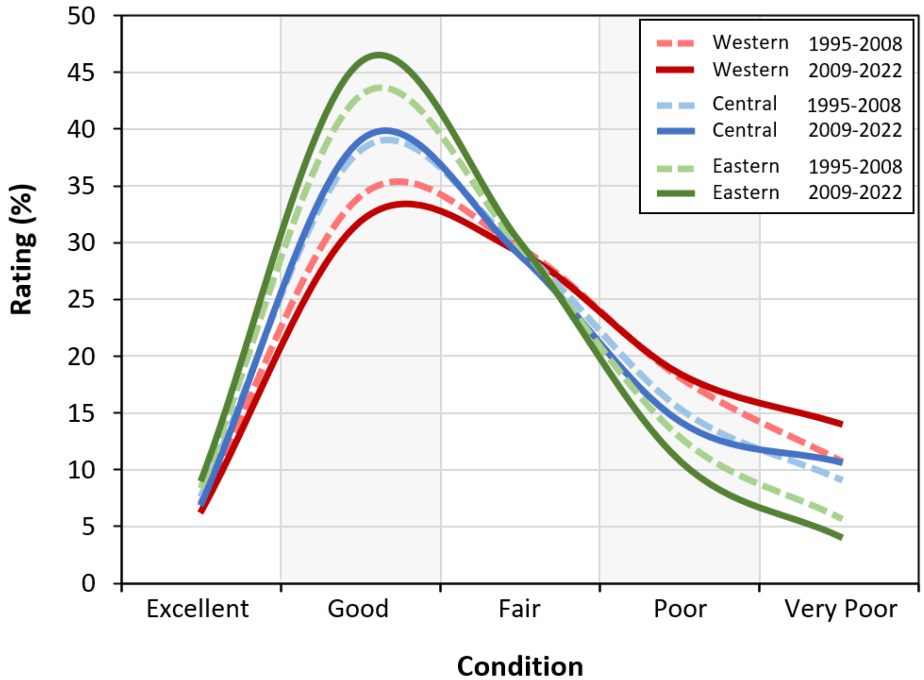


**Figure 10.** U.S. regional and warm season-averaged pasture and rangeland condition coverage averaged in two 14-year epochs (1995–2008, 2009–2022). Western United States is defined as states west of the 105th meridian; Eastern United States is defined as states east of the 95th meridian; and Central United States is defined as states between the 95th and 105th meridian.

## 4 DISCUSSION

### 4.1 Explanatory factors

Grazing land condition changes, including intraseasonal variability across states and spatiotemporal trends over time, are explained by both abiotic and biotic influences. Observed declines in grazing land conditions, on average, at the national level through the warm season (**Figure 2**) are in large part driven by vegetation response-time variability to precipitation (or lack thereof) and weather in general (Arnone et al., 2008; Wu et al., 2015). Precipitation timing and duration are the dominant climatic regulators of non-irrigated grazing land productivity

(Knapp & Smith, 2001; Sala et al., 2012; Bunting et al., 2017; White et al., 2023), and this, in conjunction with temperatures, ultimately controls soil moisture availability for plants (Sala et al., 2012; Wilcox et al., 2017). Whether it be pasture or rangeland, evidence from field-based studies have quantified that mean annual precipitation can account for up to 90% in aboveground net primary production of grasslands (Del Grosso et al., 2008; Guo et al., 2012).

In addition to precipitation, temperatures, and soil moisture, another climate variable that plays a non-trivial role in the climatology of grazing land conditions is evapotranspiration—the process by which water is transferred from land to the atmosphere by evaporation from soil and by transpiration from plants. Furthermore, evapotranspiration is the main driver of energy balance in the hydrological cycle, making it an essential component when developing strategies to improve agricultural water use (Bezerra et al., 2012). An example of how these factors control the state of grazing land conditions is by comparing the southwestern and northeastern U.S. domains. Annually, precipitation accumulation across the southwestern United States is significantly less (ranging 120–170 cm less) than the northeastern United States, on average, and average temperatures register 10°C or greater in the southwestern region than in the northeastern United States (NOAA, 2023). As a result, the estimated fraction of precipitation lost to evapotranspiration is greater than 80% in the southwestern United States, while it less than 40% in the northeastern United States on an annual basis (Sanford & Selnick, 2013). Therefore, the arid and semi-arid climates of the southwestern United States, and greater western United States, leads to grazing conditions to display lower quality grazing conditions than that of the sub-humid and humid eastern half of the nation (**Figures 3, 4, 5, 10**). As such, grazinglands across the western United States have a lower resilience to interannual precipitation deficits, or droughts (Stanimirova et al., 2019). In other words, vegetation adjustment rates to precipitation fluctuations can be low in the southwestern United States, which means lower resilience and a slower return of the grazing system to equilibrium (Stanimirova et al., 2019). This slower return is why recent droughts in the western and central portions of the United States have continued to cause grazing lands in recent years to be historically low (**Figure 6**), further impacting the climatological average and interseasonal variability of condition ratings (**Figures 3–5**) as well as the long-term condition trends (**Figures 8–10**).

Additionally, condition responses are also impacted by biotic factors such as grazing capacity, which can influence both the short- and long-term productivity of a pasture or rangeland (Illius & O'Connor, 1999; Fuhlendorf et al., 2001; Briske et al., 2003). Hence, if a pasture or rangeland is overgrazed, a decline in condition may be observed in the weekly data. Declining grazing land conditions during September and October can have major ramifications for the following seasons, especially if overgrazed—forage production can be reduced by over 50% in some states (NDSU, 2023). Thus, it is the combination of abiotic and biotic factors that makes the use of the USDA NASS condition data valuable. Moreover, the condition indices reflect the timing of degrading and improving conditions more accurately than solely examining weather, climate, and other abiotic and biotic variables alone to determine condition trends. This attributes to the high-quality network of extension agents and Farm Service Agency staff who can accurately assess the status of a field during critical periods of anomalous conditions.

### 4.2 Climate trends

Changing grazing land conditions on a weekly basis and over time can be linked with regional climatic changes across the United States. Furthermore, while short-term climatic events are important drivers of weekly grazing land condition changes and ecological transitions

(Smith, 2011), it is equally important to place extreme events within the context of long-term climate cycles and trends (Harris et al., 2018; Peters et al., 2021).

Since 1970, the rate of warming temperatures in the United States has been 60% faster than the rest of Earth (Marvel et al., 2023), and this has had implications for other components of the climate system, consequently impacting grazing land condition trends. These trends have been extensively observed across the western United States, where many states experienced a statistically significant increase in temperatures (e.g., Joyce et al., 2013; Reeves et al., 2014; Hanberry et al., 2019; McIntosh et al., 2019) and a general decline in accumulated precipitation (e.g., Easterling et al., 2017; Marvel et al., 2023). There is high confidence that heatwaves have become more common and severe across the western United States since the 1980s, and there is very high confidence that drought risk—linked with long-term aridification trends (Overpeck & Udall, 2020)—has increased over the past century; at the same time, precipitation has become more extreme in recent decades (Marvel et al., 2023).

Also of note, the 2000–2021 period in the southwestern United States contained the driest soil moisture of any period of the same length over the past 1,200 years (Williams et al., 2022), which can explain, in large part, why this region had grazing land conditions during at least 70% of warm-seasons below the national CCIndex average (**Figure 5**). Previous literature has demonstrated that arid and semi-arid global grazing lands possess nontrivial sensitivity to precipitation variation and, therefore, are vulnerable to climate change (Stanimirova et al., 2019). Drought conditions have decreased forage quality, availability, and productivity, affecting livestock operations, habitat for other species (Winford & Lee, 2021), and long-term soil integrity (Archer & Predick, 2008); this is reflected in the intermonthly and interseasonal spatiotemporal trends in grazing land conditions across the western half of the nation (**Figures 8–10**).

It is important to note that these long-term climate patterns, and patterns in seasonal grazing land conditions, can be associated with multi-year and multi-decadal climate teleconnection patterns (Christensen et al., 2023). For example, both the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) influence wet-dry cyclic patterns, directly impacting the spatiotemporal distribution of precipitation and consequently impacting vegetation productivity across the globe (e.g., Detsch et al., 2016; Chen et al., 2017; Bathiany et al., 2018; Jiao et al., 2021). This is particularly true for the southwestern domain, as previous literature has quantified the significant relationship between the PDO and perennial grass cover within the region (Christensen et al., 2023). For example, over the 1995–2022 period, the PDO transitioned from a warm to a cool phase (warmer-than-normal sea surface temperatures became anomalously cooler along coastal North America), which resulted in a decrease in perennial grass cover (Christensen et al., 2023), which is likely a direct result of the observed declines in grazing land conditions across the southwestern United States (**Figures 8 and 9**). Therefore, while this research established the monotonic trend in grazing land conditions over the 28-year period, the evident cyclic patterns in seasonal-averaged condition ratings (**Figure 6**) reveal the need for future research to continue exploring the correlation between grazing land conditions, grassland coverage, and climate teleconnection patterns like ENSO and PDO.

In addition, large fires on western U.S. grazing lands have also increased more than fivefold during the 1984–2017 epoch (Li et al., 2021)—driven in part by increases in invasive grass cover (e.g., woody plant encroachment, Russian olive) from precipitation changes—that ultimately alter the condition of grazing lands (Archer & Predick, 2008; DiTomaso, 2000;

Archer et al., 2017; Breshears et al., 2016; Bestelmeyer et al., 2018; Archer et al., 2017; Archer et al., 2023). Alongside climate change impacts, there has been a significant shift to exurban development, especially in Nevada, Arizona, and New Mexico (Archer & Predick, 2008). These arid lands are exposed to new levels of environmental pressure, including increased air pollution, atmospheric nitrogen deposition, motorized off-road vehicles, feral pets, and non-native plants (Archer & Predick, 2008).

Meanwhile, a majority of the eastern half of the United States has experienced an increase in precipitation totals (Easterling et al., 2017; Marvel et al., 2023)**,** likely contributing to general improvements in grazing land conditions (**Figures 8–10**). Average annual precipitation in the 2002–2021 period was 5%–15% higher relative to the 1901–1960 average across the central and eastern United States, a trend attributable to climate change (Knutson & Zeng, 2018). Furthermore, hydrological droughts have become less frequent in the eastern United States due to increases in precipitation that compensate for warming-driven increases in evapotranspiration (McCabe et al., 2017).

### 4.3 Implications, adaptation, and future work

The resulting grazing land condition changes across the United States has had, and will continue to have, major ramifications on the livestock industry. In the United States, cattle production is among the most important as it consistently accounts for the largest share of total cash receipts for agricultural commodities—it is forecast to represent about 17% of the 520 billion USD in total cash receipts in 2023 (ERS, 2023). This is especially important in the southwestern United States —where grazing land conditions have declined and are rated the lowest on average amongst the entire United States —as livestock production is the dominant use of agricultural land, accounting for about one-third of agricultural revenue (Havstad et al., 2018).

As a result of drought conditions in recent years, producers have been forced to reduce their livestock capacity and increase labor demands for feeding (McPherson et al., 2023), which has reduced the nation's total supply of cattle and corresponding beef products (ERS, 2023). Consequently, the decline in supply has resulted in an increase in cattle and beef prices over time (ERS, 2023). In addition to inventory declines and market price fluctuations since 1980 (ERS, 2023), producers are also faced with increasingly challenging management decisions from increasing feed costs and rising land values (Augustine, 2010; Derner & Augustine, 2016; Shrum et al., 2018). The growing list of consequences accelerates the need for useful indicators and metrics to monitor near-real-time conditions, such as the USDA NASS pasture and rangeland condition dataset, to support adaptive management practices (Bestelmeyer & Briske, 2012; Derner et al., 2012; Derner & Augustine, 2016; McCollum et al., 2017).

Although climatic impacts vary depending on pasture and rangeland types and management strategies already in place (e.g., irrigation, insurance), the likely result of future climate trends are a continuation of deteriorating grazing land conditions for some regions. Overall, the response of grazing land productivity to climate change will be influenced by grazing management and the willingness to implement adaptation strategies (Izaurralde et al., 2011). One of the applications of this research is to use these results to assist with longer-term managerial decisions for grazing land sustainability. For example, in states with a declining trend in grazing land conditions, land managers might need to provide additional forage or supplemental feed to support operations, which increases the cost of production and perhaps reduces herd size. If land managers decide to leave livestock on grazing lands for longer periods, there will be increased stress on the land, creating a risk of further degradation. In states where increases in grazing land conditions were observed, land managers may choose to increase herd size, resulting in additional economic activity (McCollum et al., 2017).

Of course, strategy implementation and needs will vary, and there is not a single solution to totally mitigate the threat of climate change on grazing conditions. For example, some livestock producers may be able to quickly adapt by implementing new strategies for dealing with declining carrying capacity, but due to ongoing drought conditions, others may be incapable of doing so because their lands are already overgrazed and cannot recover (Lengnick, 2015; Stanimirova et al., 2019). Examples of grazing land management practices include flexible stocking rates, grazing with multiple paddocks, longer rest periods for forage recovery, varied seasons of grazing, optimizing herd size and composition, employing livestock bred for arid environments, identifying reserve forage, strategic distribution of water, proactive vegetation management, erosion control, identification of alternate forage supplies, conversion to integrated crop-livestock farming systems, and changes in enterprise structure (Russelle et al., 2007; Gonzalez et al., 2018).

Additionally, a strategy to improve ranch resilience is drought planning (Lessa et al., 2020; Haigh et al., 2021), which focuses on identifying critical weeks for monitoring conditions (Smart et al., 2021) and can be used in parallel with USDA NASS weekly pasture and rangeland condition data to make informed decisions. For example, if 1) state-level grazing land conditions have declined in recent week and display a similar trend to what has been observed in at the field level within that state, 2) grazing land conditions are below average for the current week in a particular state, and 3) if the precipitation forecast in the weeks ahead suggest below average totals, then these factors may prompt the land manager to implement drought strategies. These responses may involve adjusting the number of cattle, the timing of grazing, and the length of grazing time in pastures and rangelands that is data-driven and supported by precipitation departures from normal, vegetation growth (Wilmer et al., 2018), and the grazing land condition climatology and current spatiotemporal trends established in this research.

Arguably, something that may be most important in sustainability, and something to expand upon in future research using the USDA NASS condition data, is obtaining a financial safety net through agricultural insurance. Grazing and the lack of yield measurements makes insuring pastures and rangelands with traditional insurance products generally impractical (Vroege et al., 2019). Index insurance programs rely on an endogenous index that is highly correlated to grazing land production, and can also be used in conjunction with the USDA NASS pasture and rangeland condition dataset. Another application of this research is to promote the use of these programs, including the Pasture, Rangeland, Forage (PRF) Program; Livestock Forage Disaster Program (LFP); and the Conservation Reserve Program (CRP) Grasslands, as these programs are designed to mitigate financial risk during times of unfavorable weather conditions. Therefore, given the state-level results from this research, producers should investigate the various programs available and see which can be of particular use.

Future work may involve using USDA NASS data and the newly established spatiotemporal grazing land condition climatology to continue bridging the knowledge between pasture and rangeland ecosystems to the effects of climate and livestock production. This may involve further investigating trends within each state and pinpointing the exact causes of the trends. This may also involve quantifying the specific correlation coefficients between weather and climate variables such as precipitation, temperature, and evapotranspiration with grazing land condition data to improve the predictability of condition changes on a weekly basis. Additionally, future research may involve examining pasture and rangeland plant communities, conducting a more in-depth analysis regarding the observed state-level trends, and comparing the various trends with different plant types. Finally, and as noted earlier, future research may involve examining the relationship between grazing land conditions and the short- and long-term cyclic patterns that may be correlated with teleconnection climate patterns to improve the predictability of conditions on an interannual basis.

## 5 CONCLUSIONS

With over one-third of the U.S. land area encompassed by grazingland, a cohesive understanding and establishment of the baseline climatology of pastures and rangelands is critical for advancing management operations under a changing climate. This research used data from the USDA NASS general crop condition database, which has generally been overlooked in the literature until recently (e.g., Irwin & Good, 2017a, 2017b; Irwin & Hubbs, 2018; Begueria & Maneta, 2020; Bundy & Gensini, 2022; Bundy et al., 2023, 2024), to quantify grazing land condition tendencies from May through October, quantify seasonal averages and variability for each state, and quantify spatiotemporal trends in conditions in the conterminous United States for the 1995–2022 study period.

During a given season, grazing land conditions tended to deteriorate as the amount of land providing adequate or an excess of feed (excellent or good condition) decreased by 14% on average. By the end of the warm season in October, nearly 33% of land needed supplemental feeding to maintain livestock conditions. Spatially, the southwestern United States retained the lowest conditions on average due to having at least twenty years below the U.S. average condition rating. At the national aggregated level, conditions have degraded during the 28-year study period, as the most significant trends were observed for poor or very poor condition coverage, with a total increase of 7% ($0.26\% \cdot yr^{-1}$). These robust increasing trends in poor and very poor condition coverage were most apparent across the western half of the United States (west of the 105th meridian), which is predominantly rangeland. Meanwhile, the eastern half of the United States (east of the 95th meridian), which is mostly pastureland, generally experienced an improvement in conditions.

Overall, continuing regional climatic shifts that have resulted in increasing temperatures, variable precipitation totals, and subsequent soil moisture declines leading to increased drought instances will impose new challenges for resource managers. Grazing land declines can result in increased feed supply demand and reduced grazing capacity; therefore, the need for flexible livestock, forage, and grazing management strategies will be critical in the coming decades to adapt to the impacts of climate change on water-sensitive ecosystems. These new findings will appeal to land managers and policymakers by providing material to help foster informed decision-making, prompt adaptation and management strategies, and address environmental changes and land-use demands. Additionally, these results suggest the pasture and rangeland condition data released weekly in the USDA NASS CPC report should be monitored to assist with real-time decision-making to detect degradation and encourage targeted interventions to support livestock production.

## SUPPLEMENTAL MATERIAL

Supplemental material provides specific pasture and rangeland condition percentages for each general condition category (excellent, good, fair, poor, very poor).

## DATA AVAILABILITY

Data from https://quickstats.nass.usda.gov/

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