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Simulating the Effects of Beef Cattle Stocking Rate on Bermudagrass Forage Growth and Stocker Gain as Influenced by Climate Variability and Management Strategy

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Abstract

In the southern United States, beef cattle production on pastures is a key economic activity. Here, bermudagrass [*Cynodon dactylon* (L.) Pers.] is a commonly used warm-season perennial grass for pastures. Stocking rate (SR) is a key management variable affecting forage growth and animal performance. Climate variability is a major environmental phenomenon significantly impacting agriculture in this region. Because of complex relationships between grazing systems and the environment and due to the lack of an effective investigative tool, the impacts of SR on bermudagrass forage growth and beef cattle (stocker) performance as influenced by climate variability and soil moisture condition in this region are unknown. Using a forage-animal interface model and the historical weather data spanning 76 years (1950-2025) collected at Overton, Texas, this study assessed the effects of: 1) SR on bermudagrass herbage mass (HM), the grazed HM per unit of pasture (GHM_P) and animal (GHM_A), and the seasonal weight gain (SWG) and average daily gain (ADG) of stockers as influenced by El Niño-Southern Oscillation (ENSO) and soil moisture condition in this region; and 2) drought on these variables as influenced by SR. Simulations were performed for 456 scenarios, comprising 76 years × 3 SRs (5, 8, and 11 $hd \cdot ha^{-1}$) × 2 moisture conditions (rainfed and irrigated). Results showed that the effect of SR on GHM_P, GHM_A, SWG, and ADG each was significant under all ENSO phases and moisture conditions ($p < 0.05$). However, the SR effect on HM was significant only under irrigated conditions. In significant cases, the values of HM and GHM_P increased, whereas those of GHM_A, SWG, and ADG decreased with an increase in SR. The influence of moisture condition on the SR effect was significant, whereas the influence of ENSO was not. Results further showed that, regardless of

SR, the HM loss due to drought increased exponentially with an increase in drought severity. The drought-induced losses of GHM, SWG, and ADG showed similar trends. But the losses became more evident with an increase in SR.

Keywords

Bermudagrass, Daily Gain, Drought, ENSO, Forage, Model, Stocker, Stocking Rate

1. Introduction

Beef cattle production on pastures is a major economic activity in the southern United States [1] [2]. The energy demand of grazing livestock is primarily met from forages [1]. One of the most commonly used warm-season perennial grasses for pastures across this region is bermudagrass [*Cynodon dactylon* (L.) Pers.] [3]-[5].

Stocking rate (SR) is a key management variable affecting forage growth and animal performance [6]. Climate variability is another variable that has significant impacts on agriculture in this region [7]-[12]. In the southern United States, the interannual variability of climate has been linked to an ocean-atmospheric phenomenon called El Niño-Southern Oscillation (ENSO) [13] [14]. The ENSO phenomenon has significantly affected agriculture in this region [7]. Because of the strong connection between ENSO and weather patterns in this region, an ENSO phase—El Niño, La Niña, or Neutral—may be successfully forecast up to a year in advance [15]. The ENSO information can help stakeholders in this region make decisions tailored to a specific ENSO phase and minimize the risks associated with climate variability.

The relationships among grazing systems, their components, and the environment are complex [16]. Because of this complexity and due to the lack of an effective investigative tool, the impacts of SR on bermudagrass forage growth and beef cattle (stocker) performance as influenced by interannual climate variability, particularly ENSO, and soil moisture condition in this region are still unknown.

The profitability of a forage-based animal production system essentially depends on efficient management strategies for the grazing system. Managing a grazing system efficiently requires understanding the complex forage-animal interface and its interconnected components [16]. Due to this interconnectedness, the individual components must be studied in relation to the system as a whole [17], which necessitates the use of mathematical models [18]-[20].

The main objective of this study was to assess the effects of beef cattle (stockers) SR on the herbage mass (HM) of bermudagrass forage, the grazed HM per unit of pasture (GHM_P) and animal (GHM_A), and the seasonal weight gain (SWG) and average daily gain (ADG) of the stockers as influenced by ENSO and soil moisture condition in the southern United States using a forage-animal interface model. A subsidiary objective was to assess the loss caused by drought on these variables as influenced by SR.

2. Materials and Methods

This simulation study used the Daily Gain Estimation System for Stockers (DGESS), a forage-animal interface model developed for stockers grazing bermudagrass pasture in the study region [21]. This system can help stakeholders understand the linkages between stockers and bermudagrass pasture, examine the constraints of the grazing system, assess the effects of management decisions on forage and animal production, develop tailored management strategies, and increase the performance of stockers.

The DGESS is an executable component within Decision Support System for Agrotechnology Transfer (DSSAT; http://www.dssat.net/), a popular suite of crop models [22]-[24], with the DSSAT Perennial Forage Model (PFM), the Stocker Daily Gain Model (SDGM) [25], and the Forage-Animal Interface (FAI) [21] as three different core modules (**Figure 1**). The PFM simulates growth, development, and biomass yield of forages as defined by the soil-plant-atmosphere dynamics (https://dssat.net/about/). The SDGM is based on animal's energy requirements and estimates daily gain as a function of the net energy in the diet for growth and maintenance, the net energy intake for maintenance, and the net energy available for growth. The FAI module establishes a connection between PFM and SDGM modules. The DGESS can be evaluated by using data on the average daily gain and body weight of stocker cattle and the associated bermudagrass forage mass. Model calibration, however, must be carried out with PFM and SDGM each separately before using the DGESS.

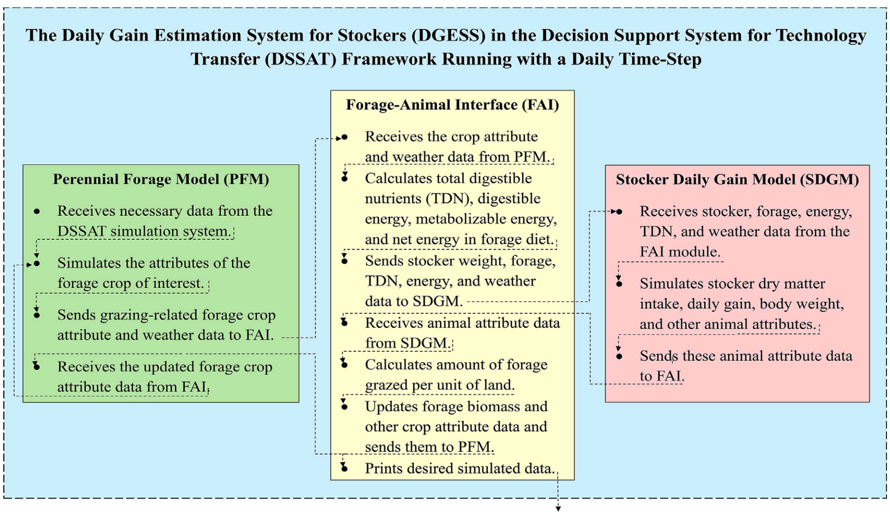

Figure 1. The Daily Gain Estimation System for Stockers. Source: [21] (P. Woli, K.J. Boote, G. Hoogenboom, C.R. Long, L.O. Tedeschi, and F.M. Rouquette Jr., "Modeling the forage-animal interface for estimating the daily gain of stocker cattle grazing bermudagrass", Journal of Animal Science, 2026, vol. 104, 1-13, by permission of Oxford University Press and the American Society of Animal Science).

2.1. Study Site

Overton (32.29˚N, 94.97˚W) in the US state of Texas, where a Texas A&M AgriLife Research and Extension Center mandated to conduct long-term forage, grazing, and beef cattle research trials and provide Extension services for the Pineywoods region in East Texas is situated, was used as a representative site for this region and the southern United States (**Figure 2**). This region covers about 141,000 km^2 in eastern Texas, southern Arkansas, and western Louisiana. Beef cattle production on pastures is a major economic activity in this region.

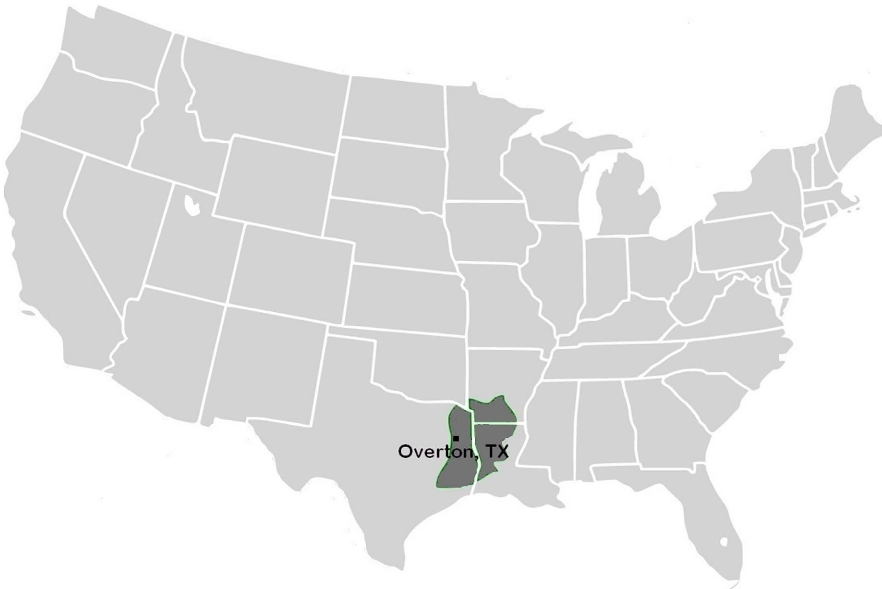

Figure 2. Map showing Overton, TX in the Pineywoods region (the darker area) of the southern United States.

2.2. Study Design

In this study, the effects of beef cattle SR on several variables associated with bermudagrass growth and stocker performance as influenced by ENSO and soil moisture conditions were assessed using the DGESS. For SR, three levels were considered: low (5 $hd \cdot ha^{-1}$), medium (8 $hd \cdot ha^{-1}$), and high (11 $hd \cdot ha^{-1}$). The body weight of each animal at stocking was assumed to be 250 kg. These numbers were based on the prevailing practices in the study region. For moisture conditions, dryland (rainfed) and fully-irrigated management strategies were studied as these options would allow one to assess the drought-induced losses of the dependent variables considered.

2.3. The Weather Data Used

The effects of SR on multiple variables as influenced by ENSO and moisture condition were studied using the long-term historical daily weather data spanning 76 years (1950-2025) collected at Overton, Texas. The weather data comprised daily values of ambient temperatures (minimum, maximum, and dewpoint), precipitation, and windspeed. The weather data were needed for simulation and drought analysis purposes. The daily values of solar radiation, another important meteorological variable for simulations, were generated using a reliable global solar radiation model for the southeastern United States [26].

2.4. Simulations

Using the DGESS, the SR effects were simulated for 456 scenarios, comprising 76 years × 3 SRs × 2 moisture conditions. Eventually, a data matrix of 456 rows and 9 columns (one for each variable: ENSO phase, SR, moisture condition, year, HM, GHM_P, GHM_A, SWG, and ADG) was created, which later was used for further analyses such as significance tests and drought effect assessments.

Of the 456 scenarios, 228 scenarios (76 years × 3 SRs) belonged to the bermudagrass forage grown under rainfed conditions and the remaining scenarios to the forage grown under irrigated conditions. While no irrigation was applied under rainfed conditions, irrigation was provided automatically so as to maintain soil moisture at the field capacity level under irrigated conditions.

2.5. Significance Tests

Using the R software environment [27], statistical significance tests were conducted to examine if the values of each of the dependent variables studied were different across the three SRs under each ENSO phase and under each soil moisture condition ($p < 0.05$). For significance tests, the pairwise Wilcoxon rank sum test [28], a non-parametric alternative to the two-sample t-test, was used, with Holm as the p-value adjustment method [29]. The tests were performed at the significance level (α) of 0.05. In this study, the Wilcoxon test was used because the assumption of normality was not met for each ENSO phase and each moisture condition for the classic "analysis of variance" test. To extract separate main effects and an interaction effect from non-normal data with multiple categorical variables, the Aligned Ranks Transformation ANOVA (ART ANOVA), a non-parametric alternative to a Two-Way ANOVA, was used. The ART ANOVA is the most robust non-parametric method for testing interactions [30] [31]. It aligns data before ranking so that main effects do not contaminate the interaction test.

2.6. Analyzing the ENSO Influence

For ENSO analyses, the 76 years (1950-2025) were assigned to a specific ENSO phase as categorized by the Japan Meteorological Agency (JMA) index [32] [33]. Based on this index, an El Niño (or La Niña) phase occurs if the 5-month running mean sea surface temperature deviation from the long-term average in the Niño 3 region (5˚S - 5˚N, 150˚W - 90˚W) is ≥0.5˚C (or ≤−0.5˚C) for at least six consecutive months. Accordingly, the total number of years available under El Niño, La Niña, and Neutral phases during the 1950-2025 period was 22, 18, and 36, respectively. For ENSO classification, the JMA index was used as it is more sensitive to El Niño and La Niña conditions than other similar indices [34]. The ENSO influence was studied under rainfed conditions only, as irrigated conditions would mask the ENSO effect.

2.7. Analyzing the Drought Effect

For drought effect analyses, the Agricultural Reference Index for Drought (ARID) [35] was used. The ARID is computationally simple, physically and physiologically sound, and generally applicable to a wide range of crops, soils, topographies, and management to characterize an agricultural drought [36]. The values of ARID range from zero, meaning no water stress, to one, meaning complete water stress. From the daily weather data, the daily values of ARID were computed for all 76 years (seasons), which then were averaged over the grazing season (May 15 through October 31) to convert them into the seasonal values. Accordingly, there were 76 ARID values available for drought effect analyses.

To truly represent the effect of water stress on an agricultural commodity, its relative value must be used [37]. This relative value is the amount of a commodity produced under water-stressed conditions relative to that which could be produced under non-water-stressed conditions, the other inputs or factors remaining the same. This relative value was obtained by dividing the water-stressed amount by the non-water-stressed amount. This division process eliminated the effects of the other factors involved, except water, thus representing the effect of only water stress on the produce.

To assess the effects of drought on HM, GHM, SWG, and ADG as influenced by SR, the relative values of a given variable were calculated for each SR by dividing its corresponding rainfed values by irrigated ones (Equation (1)).

$$ {}^{R}V_{y,s} = \frac{{}^{U}V_{y,s}}{{}^{I}V_{y,s}}, \tag{1} $$

where ${}^{R}V_{y,s}$, ${}^{U}V_{y,s}$, and ${}^{I}V_{y,s}$, respectively, are the relative, unirrigated (rainfed), and irrigated values of a given variable (V: HM, GHM, SWG, or ADG) in the y-th year under the s-th SR.

The relative values were then subtracted from 1.0 to compute the fraction of loss of that variable due to drought (Equation (2)).

$$ {}^{L}V_{y,s} = 1 - {}^{R}V_{y,s}, \tag{2} $$

where ${}^{L}V_{y,s}$ is the drought-induced loss fraction of the variable V in the y-th year under the s-th SR. Accordingly, there were 76 ${}^{L}V$ values available for drought effect analysis for each variable under each SR. Finally, these fractional values were converted into percentages by multiplying the former by 100.

3. Results and Discussion

3.1. Stocking Rate Effects as Influenced by Soil Moisture Condition

Under irrigated conditions, the SR effect on bermudagrass HM produced was statistically significant ($p < 0.05$) (**Table 1**). The values of HM produced increased considerably with an increase in SR (**Figure 3**). The likely reasons for this increase were as follows. As stated above, the three SRs considered for the study belonged to moderate grazing. Under moderate grazing, animals remove about 40% to 50% of the annual forage growth, opening up the canopy and allowing sunlight to reach the base of the plant [38] [39]. This grazing intensity acts as a catalyst for growth and stimulates dormant buds to produce new vegetative shoots and diverts energy toward active, nutritious leaf production rather than reproductive stem growth [38]-[41]. At low stocking (light grazing), animals select a small fraction of the available forage, leaving most of the leaf canopy intact and letting plants prioritize vertical stem elongation and flowering and ungrazed canopies restrict new basal leaf development [42]-[44].

Table 1. The effect of stocking rate on various variables associated with bermudagrass herbage mass (HM) and stocker performance as influenced by El Niño-Southern Oscillation and soil moisture condition at Overton, Texas, USA during 1950-2025.

Factor	Level	Variable	Unit	Stocking rate ($hd \cdot ha^{-1}$)		
				5	8	11
Soil moisture condition	Irrigated	Bermudagrass HM produced	$kg \cdot DM \cdot ha^{-1}$	14,841^{c*}	15,801^{b}	17,101^{a}
		HM grazed per unit of pasture	$kg \cdot DM \cdot ha^{-1}$	6652^{c}	10,524^{b}	13,790^{a}
		HM grazed per animal	$kg \cdot DM \cdot hd^{-1}$	1331^{a}	1316^{b}	1254^{c}
		Stocker seasonal weight gain	$kg \cdot BW \cdot hd^{-1}$	146^{a}	139^{b}	131^{c}
		Stocker average daily gain	$kg \cdot BW \cdot hd^{-1}$	0.86^{a}	0.82^{b}	0.77^{c}
	Dryland	Bermudagrass HM produced	$kg \cdot DM \cdot ha^{-1}$	11,087^{a}	11,562^{a}	11,616^{a}
		HM grazed per unit of pasture	$kg \cdot DM \cdot ha^{-1}$	6291^{c}	8931^{b}	9998^{a}
		HM grazed per animal	$kg \cdot DM \cdot hd^{-1}$	1258^{a}	1116^{b}	909^{c}
		Stocker seasonal weight gain	$kg \cdot BW \cdot hd^{-1}$	133^{a}	103^{b}	66^{c}
		Stocker average daily gain	$kg \cdot BW \cdot hd^{-1}$	0.78^{a}	0.61^{b}	0.39^{c}
El Niño-Southern Oscillation (ENSO)	El Niño	Bermudagrass HM produced	$kg \cdot DM \cdot ha^{-1}$	10,998^{a}	11,396^{a}	11,375^{a}
		HM grazed per unit of pasture	$kg \cdot DM \cdot ha^{-1}$	6336^{c}	8976^{b}	9937^{a}
		HM grazed per animal	$kg \cdot DM \cdot hd^{-1}$	1267^{a}	1122^{b}	903^{c}
		Stocker seasonal weight gain	$kg \cdot BW \cdot hd^{-1}$	136^{a}	105^{b}	66^{c}
		Stocker average daily gain	$kg \cdot BW \cdot hd^{-1}$	0.80^{a}	0.62^{b}	0.39^{c}
	La Niña	Bermudagrass HM produced	$kg \cdot DM \cdot ha^{-1}$	10,424^{a}	10,884^{a}	11,005^{a}
		HM grazed per unit of pasture	$kg \cdot DM \cdot ha^{-1}$	6118^{c}	8431^{b}	9454^{a}
		HM grazed per animal	$kg \cdot DM \cdot hd^{-1}$	1224^{a}	1054^{b}	859^{c}
		Stocker seasonal weight gain	$kg \cdot BW \cdot hd^{-1}$	130^{a}	91^{b}	54^{c}
		Stocker average daily gain	$kg \cdot BW \cdot hd^{-1}$	0.77^{a}	0.54^{b}	0.32^{c}

Continued

	Bermudagrass HM produced	kg·DM·ha⁻¹	11,473[a]	12,003[a]	12,069[a]
	HM grazed per unit of pasture	kg·DM·ha⁻¹	6349[c]	9153[b]	10,308[a]
Neutral	HM grazed per animal	kg·DM·hd⁻¹	1270[a]	1144[b]	937[c]
	Stocker seasonal weight gain	kg·BW·hd⁻¹	133[a]	108[b]	72[c]
	Stocker average daily gain	kg·BW·hd⁻¹	0.78[a]	0.64[b]	0.42[c]

*Means followed by the same letter across stocking rates (horizontally) within a factor-level-variable combination are not significantly different at the significance level (α) of 0.05.

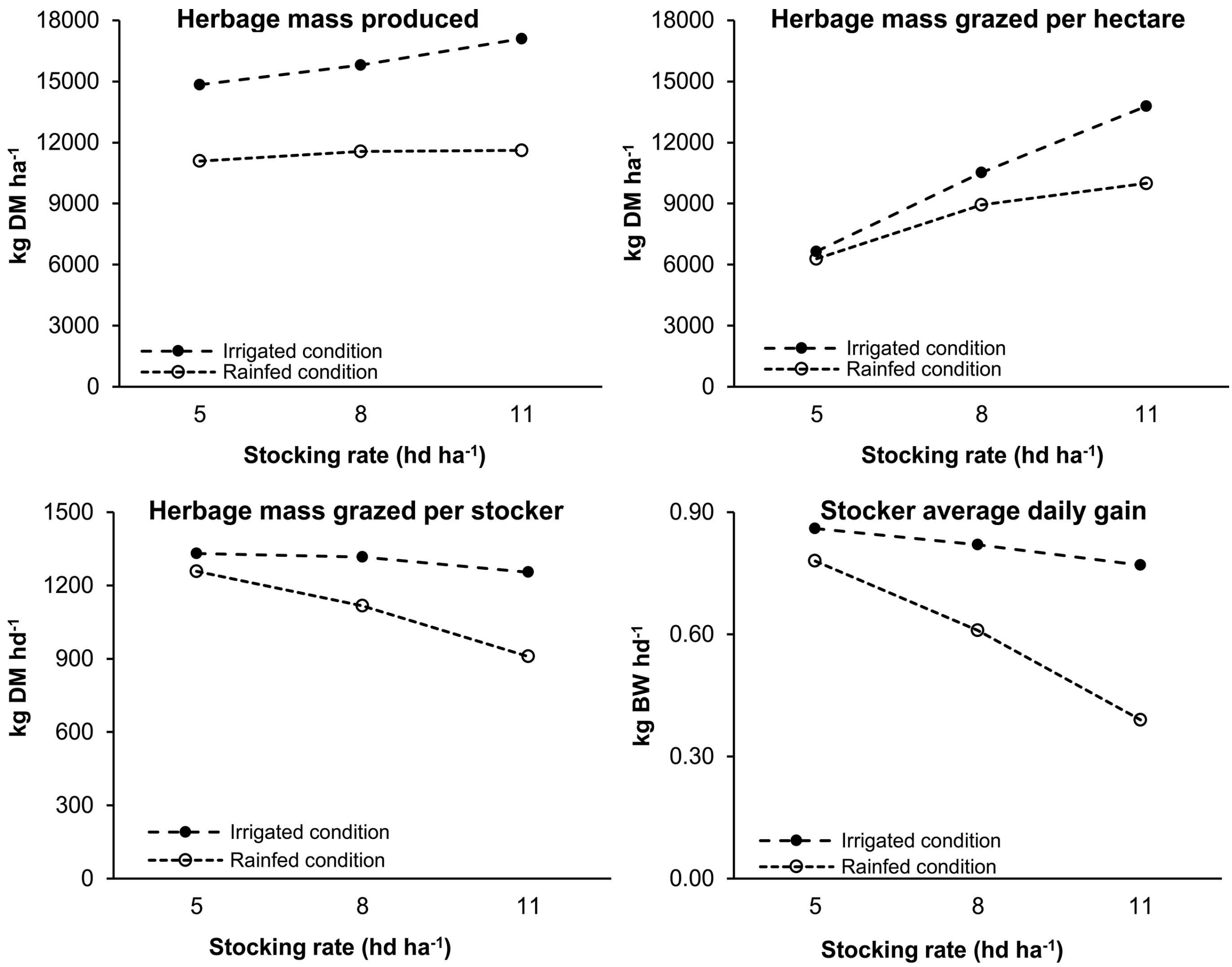

Figure 3. Effects of stocking rate on bermudagrass herbage mass produced and grazed and the average daily gain of stockers under irrigated and rainfed conditions at Overton, TX, USA during 1950-2025.

With an increase in SR within moderate grazing, animals defoliate more forage, and more new vegetative shoots and nourishing leaves are produced. An increase in leaf mass but a decrease in stem mass with an increase in SR confirmed these phenomena (Figure 4). The significant increase in HM with increased SR under irrigated conditions was due to non-water-limited production conditions. Under these conditions, the potential benefits of moderate grazing and other inputs, such as manures and fertilizers, were fully realized.

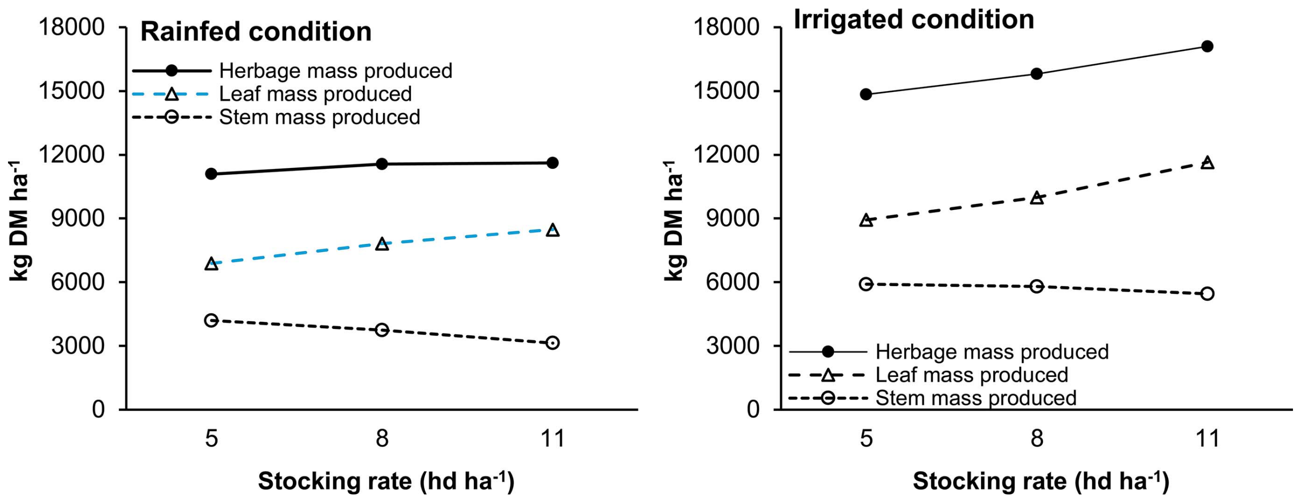

Figure 4. Effects of stocking rate on the bermudagrass herbage mass, leaf mass, and stem mass produced under rainfed and irrigated conditions at Overton, TX, USA during 1950-2025.

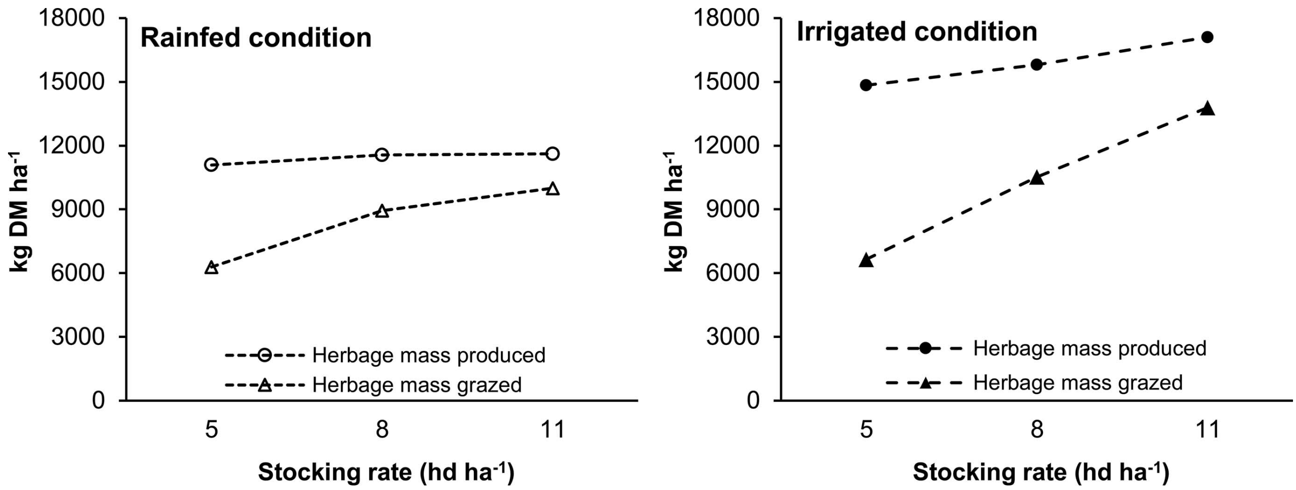

Figure 5. Effects of stocking rate on bermudagrass herbage mass produced and grazed under rainfed and irrigated conditions at Overton, TX, USA during 1950-2025.

Under rainfed conditions, the effect of SR on bermudagrass HM was not statistically significant ($p > 0.05$), but the HM values tended to increase with an increase in SR (Table 1). As discussed above, this pattern was likely because of stimulated new leaf growth and tillering under moderate grazing [38]-[41]. The non-significant increase in HM with increased SR, however, was due to dryland conditions. Water limitation reduced leaf growth and tillering stimulated by an increase in defoliation.

Under both rainfed and irrigated conditions, the effect of SR on GHM_P, GHM_A, SWG, and ADG each was significant (Table 1). With an increase in SR, the values of GHM_P increased, whereas those of GHM_A, SWG, and ADG decreased significantly (Figure 3). However, the increase in HM grazed per hectare (GHM_P) was linear under irrigated conditions but curvilinear under rainfed conditions (Figure 5). The increase in GHM_P with increased SR under both conditions was due to more animals on a pasture consuming a larger quantity of HM on that pasture. The curvilinear increase in GHM_P under rainfed conditions was likely because the HM produced was almost constant across all SRs. This situation led to the plateauing of the HM grazed (Figure 5). With an increase in SR, the animal grazing need increased, but the forage availability did not change much. The linear increase in GHM_P under irrigated conditions was due to the following reasons. The HM produced linearly increased with SR for the reasons explained in previous paragraphs. This situation did not allow for the plateauing of the HM grazed. The animal grazing needs increased linearly with SR, and so did the availability of forage for grazing (Figure 5).

The gap (difference) in each variable (bermudagrass HM, GHM_P, GHM_A, SWG, or ADG) between rainfed and irrigated conditions increased with an increase in SR (Figure 3). These trends as well as the p-values presented in the ART ANOVA tables (Table 2) indicated that the SR effect was significantly influenced by soil moisture conditions ($p < 0.05$). The SR effect was stronger under high moisture (irrigated) conditions. The slopes of HM and GHM_P to SR were steeper under irrigated conditions than those under rainfed conditions, whereas the slopes of GHM_A, SWG, and ADG to SR were steeper under rainfed conditions than those under irrigated conditions.

Table 2. The ART ANOVA tables showing the main effects of stocking rate (SR) as well as the interaction effects between SR and MC (soil moisture condition) or ENSO (El Niño-Southern Oscillation) on various variables associated with bermudagrass herbage mass and stocker performance at Overton, Texas, USA during 1950-2025.

Variable	Term	DF*	DF Res.	Sum Sq.	Sum Sq. Res.	F-value	Pr (>F)
Herbage mass (HM)	SR	2	438	804,128	6,647,223	26.49	1E−11
	SR:MC	2	438	491,428	7,032,117	15.30	4E−07
	SR:ENSO	4	438	795	7,552,907	0.01	1.00
	SR:MC:ENSO	4	438	4251	7,541,007	0.06	0.99
Grazed HM per unit of pasture (GHM_P)	SR	2	438	4,773,737	2,543,471	411.03	3E−101
	SR:MC	2	438	1,831,988	5,405,398	74.22	2E−28
	SR:ENSO	4	438	154,397	7,013,370	2.41	0.10
	SR:MC:ENSO	4	438	112,195	7,056,563	1.74	0.14
Grazed HM per animal (GHM_A)	SR	2	438	2,261,593	4,948,480	100.09	2E−36
	SR:MC	2	438	1,415,708	5,740,081	54.01	1E−21
	SR:ENSO	4	438	55,974	6,981,305	0.88	0.48
	SR:MC:ENSO	4	438	25,011	6,991,101	0.39	0.81

Continued

Seasonal weight gain (SWG)	SR	2	438	1,972,578	5,080,463	85.03	6E−32
	SR:MC	2	438	912,240	6,266,580	31.88	1E−13
	SR:ENSO	4	438	122,846	6,988,590	1.92	0.11
	SR:MC:ENSO	4	438	30,552	7,083,982	0.47	0.76
Average daily gain (ADG)	SR	2	438	1,979,018	5,077,921	85.35	5E−32
	SR:MC	2	438	903,762	6,264,749	31.59	2E−13
	SR:ENSO	4	438	126,988	6,980,298	1.99	0.10
	SR:MC:ENSO	4	438	26,265	7,080,807	0.41	0.80

*DF = degrees of freedom, Res. = residuals, Sq. = square, Pr (>F) = p-value.

3.2. Stocking Rate Effects as Influenced by ENSO

The effect of SR on bermudagrass HM was not statistically significant under each ENSO phase (**Table 1**). However, the HM values tended to be larger with an increase in SR. This pattern was likely because moderate grazing stimulated new leaf growth and tillering [38]-[41]. However, the HM increase with an increase in SR within moderate grazing was not significant because of dryland conditions. The shortage of sufficient soil moisture, as the limiting factor for forage production, led to insignificant new leaf growth and tillering.

However, the effect of SR on GHM_P, GHM_A, SWG, and ADG each was significant under all ENSO phases (**Table 1**). That is, with an increase in SR, the values of GHM_P increased significantly, whereas those of GHM_A, SWG, and ADG had significant decreases (**Figure 6**). In the case of GHM_P, its values increased at a decreasing rate with an increase in SR. The likely reason for this increase was as follows. As expected, more animals on a given pasture consumed a larger amount of HM on that pasture as long as the pasture had enough herbage allowance to sustain the grazers. However, with an increase in SR, the availability of forage for grazing, that is, the HM produced per unit of the HM grazed (needed by the animals) or the gap between the HM produced on a pasture and the HM grazed on that pasture, became less (**Figure 7**).

With the amount of HM produced on a pasture being almost constant at all SRs, the herbage allowance (HM per animal) decreased with an increase in SR. Accordingly, the amount of HM grazed by each stocker (GHM_A) also decreased. The decrease in GHM_A, in turn, led to the decrease of both SWG and ADG.

Although the value of each dependent variable under La Niña was the smallest of all the ENSO phases at each SR (**Figure 6**) due to the driest grazing conditions (represented by the greatest seasonal average value of ARID) under this phase (**Figure 8**), the differences (gaps) in each variable across the ENSO phases at each SR were not significant ($p > 0.05$). Moreover, these ENSO gaps across SRs were about the same (**Figure 6**). These trends as well as the p-values presented in

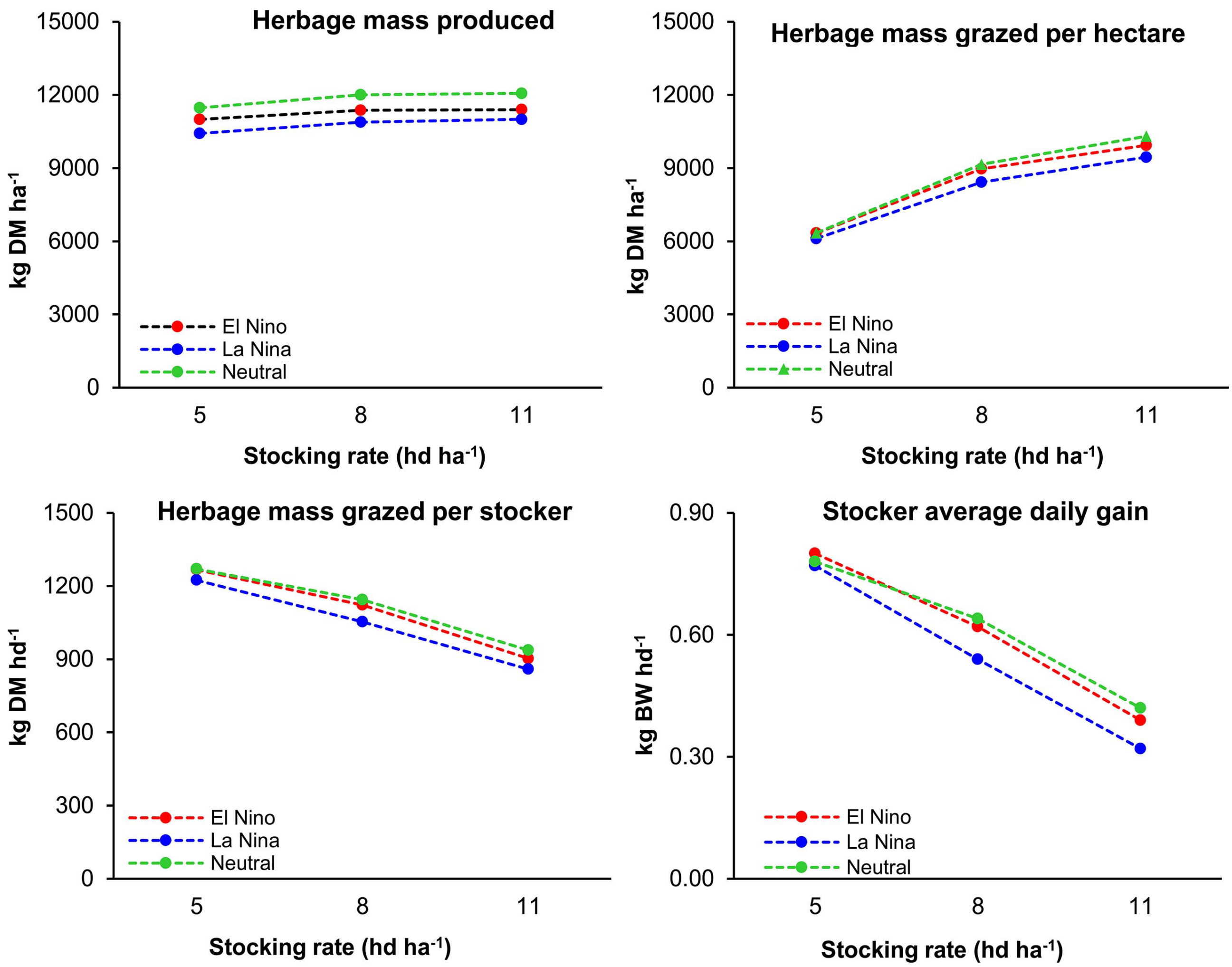

Figure 6. Effects of stocking rate on bermudagrass herbage mass produced and grazed and the average daily gain of stockers under three ENSO phases at Overton, TX during 1950-2025.

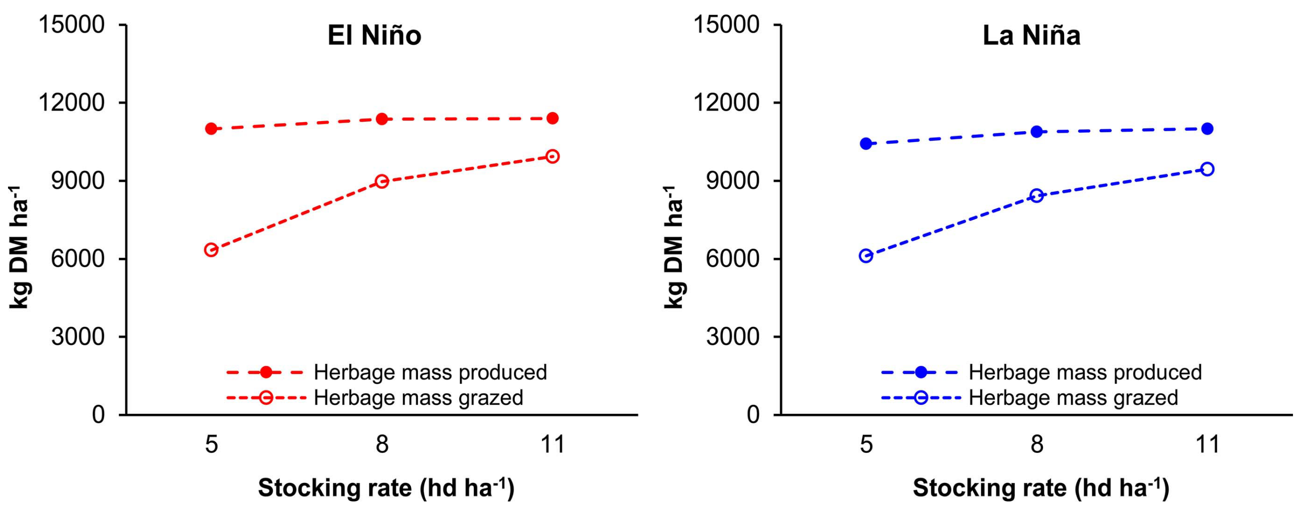

Figure 7. Effects of stocking rate on bermudagrass herbage mass produced and grazed under the El Niño and La Niña phases of ENSO at Overton, TX, USA during 1950-2025.

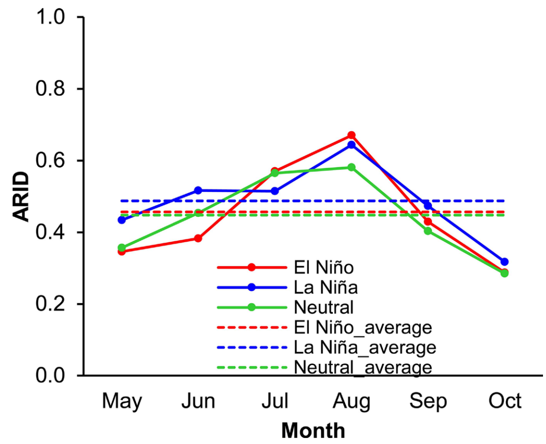

Figure 8. The El Niño-Southern Oscillation (ENSO) phase-specific monthly and seasonal average values of the drought index ARID at Overton, TX, USA during 1950-2025.

the ART ANOVA tables (Table 2) suggested that the SR effect on HM, GHM_P, GHM_A, SWG, and ADG each was not significantly influenced by ENSO ($p > 0.05$).

The likely reason for non-significant ENSO influence was that, although the sub-seasonal (monthly) weather conditions represented by ARID were considerably different across the ENSO phases, the seasonal average values of weather conditions did not significantly vary across the ENSO phases (the dotted lines in Figure 8). Since this study involved the seasonal values of dependent variables, they were naturally impacted by the seasonal average weather conditions.

3.3. Drought Effects as Influenced by Stocking Rate

The loss of bermudagrass HM due to drought increased exponentially with an increase in drought intensity, represented by the larger values of the drought index ARID (Figure 9). This exponential relationship between ARID and HM loss was expected. Previous researchers have also demonstrated that the relationship between drought intensity and forage production is strongly non-linear and negative. As drought severity increases, forage biomass declines sharply, often by more than 50% in arid environments. As water scarcity worsens, plant growth stunts, root systems impair, and cellular functions collapse, thus severely limiting the available biomass for livestock [45]-[48]. Incremental increases in drought intensity limit the water available for photosynthesis [45] [49]. Forage plants exhibit leaf rolling, drooping, and accelerated senescence to conserve water, directly shrinking the total herbage mass [47] [50] [51]. Research has shown that under critical drought intensity, biomass drops steeply, leaving grasslands with depleted forage [52] [53].

Results further showed that the relationship between ARID and the drought-induced loss of HM was independent of SR. That is, the HM loss caused by drought was not influenced by SR. This result was expected because the total HM produced in a season was the sum of total HM grazed by the animals during that season and the leftover HM after the grazing season. Although the total HM grazed during a given grazing season (GHM_P) was larger with a higher SR (Figure 5), the residual HM after the grazing season decreased with an increase in SR. Thus, the amounts of total HM produced in a season were about the same across SRs.

The drought-induced losses of grazed herbage mass (GHM), including both GHM_P and GHM_A, SWG, and ADG also showed similar trends. These results were likely because, regardless of SR, these variables were based on the total amount of HM produced in the grazing season, the loss of which had an exponential relationship with drought severity. However, the loss trends became more pronounced with an increase in SR (Figure 9) because the values of each of these variables under rainfed conditions relative to those under irrigated conditions decreased quadratically with an increase in SR. The above results further validated the robustness of the DGESS interface model [21].

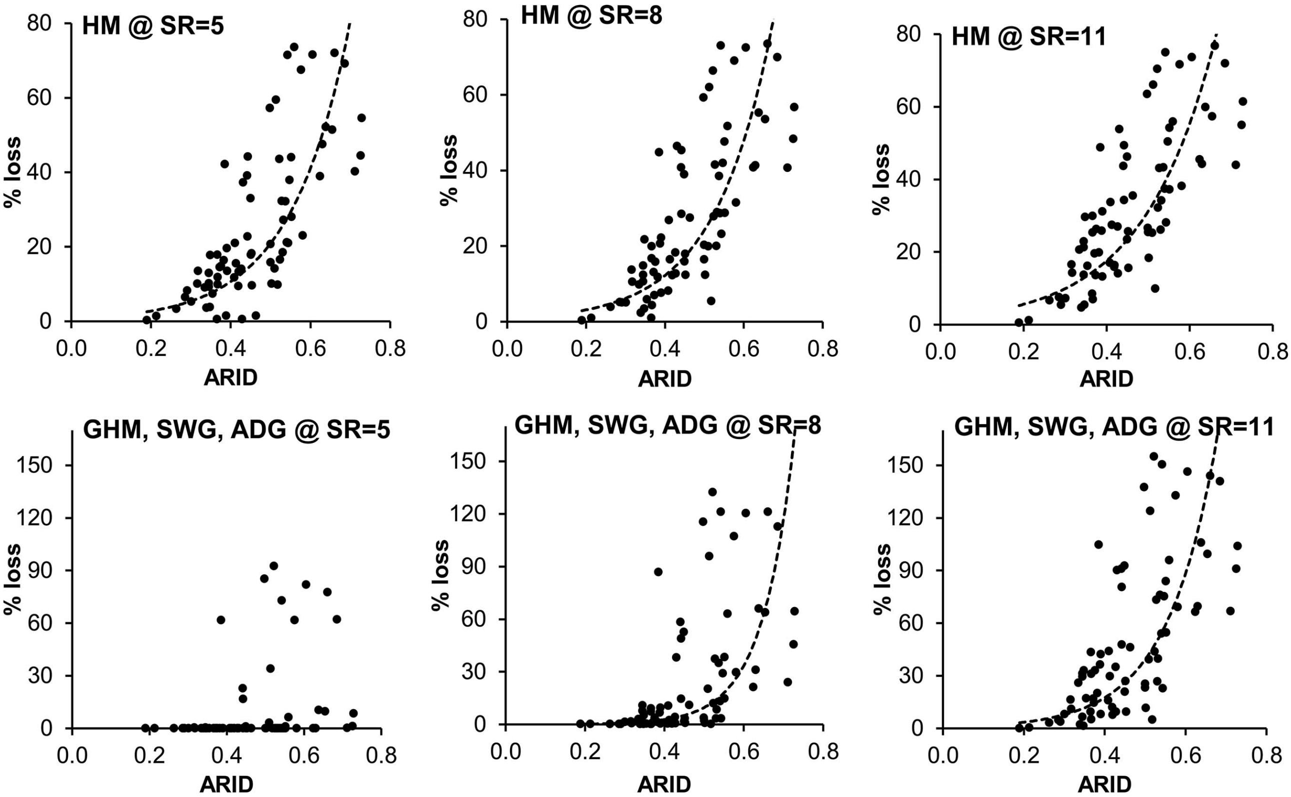

Figure 9. Relationships between the drought index ARID values and the drought-induced loss of bermudagrass herbage mass (HM), grazed HM (GHM), and stocker seasonal weight gain (SWG) and average daily gain (ADG) at three stocking rates (SR) at Overton, TX, USA during 1950-2025. The dots and dotted lines in figure represent magnitudes and trends, respectively.

4. Conclusions

This study assessed the influences of El Niño-Southern Oscillation (ENSO) and soil moisture condition in the southern United States on the effects of beef cattle stocking rate on bermudagrass herbage mass produced and grazed and stocker performance using a forage-animal interface model and long-term historical weather data. This study also examined the impact of drought on these variables as influenced by stocking rate. The simulation results showed that with an increase in stocking rate, the values of herbage mass produced and grazed increased, whereas those of stocker performance decreased. The influence of moisture condition on the stocking rate effect was significant, whereas the influence of ENSO was not. Results further showed that, irrespective of stocking rate, the herbage mass loss due to drought increased exponentially with an increase in drought intensity. The drought-induced losses of grazed herbage mass and stocker performance showed similar trends. The losses were more pronounced with an increase in stocking rate. These findings can help stakeholders develop tailored management strategies for stockers grazing bermudagrass pastures.

It should be noted, however, that as these findings are based on the stocking rates belonging to moderate grazing, the prevailing grazing intensity level in the southern United States, they may be less applicable to other grazing intensities, such as light or heavy grazing. Moreover, as this study involved a single site in the Pineywoods region due to the unavailability of continuous, long-term historical weather data in other places in the region, the findings will be more applicable to this or similar regions than others. Similarly, this study considered just one irrigation level (full) to compare non-water-limited grazing scenarios with water-limited ones to assess drought impacts. Furthermore, this study used one level of initial stocker weight and three levels of stocking rate. While these levels were enough to fulfill the scope of this study, the horizons of findings could certainly be broader with the inclusion of more levels.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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