Stocking rate impacts performance and economics of grazing beef steers on mixed-grass prairies of the Southern Great Plains[1]

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ABSTRACT: Stocking rate is a fundamental management factor that has major impacts on animal performance, profitability, and long-term sustainability of native range ecosystems. This research was conducted to determine the effects of stocking rate on performance and economics of growing steers grazing a mixed-grass prairie on a rolling upland red shale ecological site at the Marvin Klemme Range Research Station (35° 25′ N 99° 3′ W). The recommended sustainable stocking rate at this location is suggested to be 25 animal unit days (AUD)/ha. Steers [n = 836, initial body weight (BW) ± SD = 216 ± 11.7 kg] grazed at seven stocking rates ranging from 4.13 ha/steer to 1.83 ha/steer over a 7-yr period, from 1990 to 1996, with year considered the random replication. During the experimental period, overall climatic conditions were favorable for forage production with average growing season precipitation of 118% of the long-term average over the 7-yr experiment, and only 1 yr (1994 with only 57% of the long-term average) with growing season precipitation substantially less than the long-term average. Over the entire summer grazing season, average daily gain (ADG) decreased linearly ($P < 0.01$) with increasing stocking rate, such that for each additional hectare available per steer ADG increased by 0.05 kg/d (R^2 = 0.88). Contrary to ADG, BW gain per hectare over the grazing season increased linearly ($P < 0.01$) with increasing stocking rate, as stocking rate increased from 4.13 ha/steer to 1.83 ha/steer BW gain per hectare doubled from 33.1 kg/ha to 66.8 kg/ha, respectively. With land costs included in the economic analysis, net return per hectare increased linearly ($P < 0.01$) from $13 [U.S. Dollars [USD]) at the 4.13 ha/steer to $52/ha at the 1.83 ha/steer. For each additional hectare per steer, net return was reduced by $15.80 (USD)/steer and $15.70 (USD)/ha. In favorable climatic conditions, such as during this 7-yr experiment, economically optimal stocking rates can be more than doubled compared with the stocking rate recommended by the United States Department of Agriculture (USDA) Soil Conservation Service. Increasing stocking rates decrease individual animal performance but maximize BW gain per hectare, which leads to the increasing economic returns observed. Research is needed to determine the long-term implications of these stocking rates during unfavorable growing conditions and setting stocking rates based on seasonal weather patterns and extended weather outlook predictions.

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INTRODUCTION

Stocking rate is the fundamental management factor under producer control that has a major impact on animal performance (Beck et al., 2013), producer profitability, and long-term sustainability of native range-based ecosystems (Holechek et al., 1998). As the stocking rate increases, individual animal growth rates decline (Heitschmidt et al., 1990; McCollum et al., 1999; Sims and Gillen, 1999; Gunter et al., 2005), due to increased competition for preferred herbage among individuals and subsequently reduced diet quality. Yet, as stocking rates increase total body weight (BW) gain per unit of land area increases (McCollum et al., 1999; Sims and Gillen, 1999; Gunter et al., 2005) up to the point that individual animal growth rates become so low the total BW gain per unit land area begins to decline (Riewe et al., 1961; Holechek et al., 1998; Gunter et al., 2005). Generally, the influence on animal performance is much less when moving from light to moderate stocking rate compared with moving from moderate to heavy stocking rates (Holechek et al., 1998). Economic returns in cow-calf operations typically increase with heavy grazing intensity (50% to 55% forage use), but with increased financial risk and susceptibility to drought and other adverse climatic events (Heitschmidt et al., 1990; Sims and Gillen, 1999) compared with moderate use (40% to 45% forage use).

Producers are under significant economic pressures to maximize production per area in an effort to maximize returns, which can prove harmful to rangeland condition, where preferred forage species are overgrazed and decline in the sward. Increasing stocking rates of growing steers during a November to September grazing period from 41 to 82 animal unit days (AUD)/ha on mixed-grass prairie in northwest Oklahoma resulted in decreased BW gain per animal but increasing BW gain and net return per hectare (Sims and Gillen, 1999). Increasing stocking rates also increased the variability of steer BW gain, which is indicative of increasing production risk with systems having heavy forage utilization due to increased risk of destocking or feed substitutions (Heitschmidt et al., 1990). Currently, there is scant knowledge of how increased stocking rates in a summer grazing stocker operation influence individual animal performance, the productivity of land, and the economic returns of stocker cattle grazing mixed-grass prairie on the Southern Great Plains.

The objectives of the current research were to measure the effect of stocking rate on performance and economics of the stocker cattle enterprise for growing steers grazed during the summer growing season on mixed-grass prairie.

MATERIALS AND METHODS

All procedures for animal care and management in the following experiments were in accordance with accepted guidelines at the time the study was conducted (Consortium, 1988). Cattle used in this experiment were handled in such a way that unnecessary discomfort was avoided, and procedures were approved by the Oklahoma State University Institutional Animal Care and Use Committee.

Study Area

The study site and weather conditions were previously described by Gillen et al. (2000). Briefly, the Marvin Klemme Range Research Station is located 10 km northwest of Bessie, Oklahoma (35° 25′ N 99° 3′ W). This site is characterized by rolling Red Shale uplands (2% to 15% slopes) dissected by deep drainages with Cordell silty clay loam soils, which are shallow (25 to 36 cm) and contain numerous rocky outcrops of hard red siltstone. These Red Shale sites support mixed-grass prairie as the potential climax natural vegetation (Gillen et al., 2000).

The effect of these stocking rates over the 7-yr experiment at this site on standing crop dynamics and species composition was previously published by Gillen et al. (2000) and the major grass species identified on this site in 1990 were sideoats grama [*Bouteloua curtipendula* (Michx.) Torr.] 20.8 ± 2.9% composition; 27.1 ± 6.5% other short grass native species including buffalograss [*Buchlöe dactyloides* (Nutt.) Englem.], with lesser amounts of blue grama [*B. gracilis* (Willd. ex Kuth) Lag. Ex Griffiths] and hairy grama [*B. hirsuta* Lag.]; 6.8 ± 2.7% silver bluestem [*Bothriochloa saccharoides* (Sw.) Rydb.]; 5.2 ± 2.9% red threeawn [*A. purpurea* Nutt.]; and 2.0 ± 0.8% tall grass species, primarily little bluestem [*Schizachyrium scoparium* (Michx.) Nash.]. The major forbs (20.2 ± 6.3% of species composition) identified by Gillen et al. (2000) included: western ragweed [*Ambrosia psilostachya* DC.] and curlycup gumweed [*Grindelia squarrosa* (Pursh.) Dun.]. Broom snakeweed [*Gutierrezia sarothrae* (Pursh) Britt. & Rusby], a poisonous plant, was found in scattered areas and contributed 3.9% ± 1.7% of species composition (Gillen et al., 2000). The study area was divided into seven 40- to 57-ha pastures.

Treatments and Calf Management

Weaned beef steers (n = 836, BW ± SD = 216 ± 11.7 kg) were acquired from cooperating producers and were placed on pastures stocked at 1.83, 1.91, 2.29, 2.76, 3.04, 3.61, or 4.13 ha per steer. Stocking rates were maintained on the same pasture for each year of the study in order to determine the long-term effects of these particular stocking rates on forage production and rangeland condition (published in Gillen et al., 2000). This experiment was not replicated in space but was conducted from April to September of each year from 1990 through 1996 with year considered the random replication. Following removal of steers in late September each year, no more use by livestock occurred on these pastures until the following spring with the onset of the next year's experiment in April.

Steers used in this experiment were of *Bos taurus* × *Bos indicus* breeding with maximum 12.5% *Bos indicus* heritage, being typical of commercial stocker cattle sourced from the Southeastern United States. In order to equally allocate steers to pasture equalizing average BW, steers were classified into 23 kg BW groups and randomly allocated to pastures from each BW classification. Steers were offered a non-medicated complete mineral mixture ad libitum in weather-vane style feeders throughout the experiment, but no other supplemental feed was offered. Steers were implanted with 200 mg progesterone and 20 mg estradiol benzoate (Synovex-S, Zoetis Animal Health, Parsippany, NJ) at the start of each grazing season and were weighed following a 16-h removal from pasture and restriction from water at the beginning of each grazing season, in mid-July, and at the end of the grazing season in late September each year.

In order to calculate forage demand on a standardized basis, AUD was calculated for each pasture each year during the experiment, the actual BW of the steers on pastures in each year were used to calculate grazing days on an "animal unit equivalent" basis. An animal unit is defined (Allen et al., 2011a, b) as a 500 kg mature non-lactating cow in the middle third of pregnancy. It is assumed that metabolic requirements are based on the average metabolic BW of the animal, thus the steer animal unit equivalent was calculated by Animal Unit Equivalent = Steer $BW^{0.75}$ / $500^{0.75}$. In order to daily forage demand, the total number of AUD/hectare was calculated using the number of calendar days of grazing multiplied by the animal unit equivalents divided by the number of hectares in the pasture. Based on initial BW, this produced stocking rates ranging from 23 to 51 AUD/ha, the recommended sustainable stocking rate for this site was 25 AUD/ha based on United States Department of Agriculture (USDA) Soil Conservation Service (SCS, 1960) estimates. Seasonal forage demand for each stocking rate was calculated based on the average steer BW for each pasture during each year and is expressed as AUD/ha.

Economic Analysis

Enterprise budgeting techniques were used with data collected during the experiment to estimate expected values for production costs, revenue, and net return for each pasture represented by each stocking rate in hectare/steer (AAEA, 2000). Purchase and sales prices of steers were based on the 10-yr average prices for Oklahoma livestock markets for the BW classifications from 2009 to 2018, with purchase of 205 kg steers in March and sale of 340 kg steers in October (USDA AMS, 2020), adjusted using a $0.22/kg slide. Cost of mineral was based on retail prices of $0.82/kg and a targeted intake of 114 g/steer daily. Cost of inputs for daily management was estimated to be $0.10/steer. Receiving costs of steers was estimated to be $76/steer, using retail costs of dewormer, feed, implants, vaccines, and antibiotics based on 50% first pulls and 25% second pulls for bovine respiratory disease morbidity (Beck et al., 2019) and 3% death loss during receiving. Enterprise budget analysis was conducted with and without an annual land cost set at $27.17/ha, based on rental rates published by the USDA NASS (2015) in order to estimate optimal stocking rates based on net returns for producers that are renting land resources or have ownership of land without an annual land expense.

Statistical Analysis

The R software was used for all statistical analysis (R Core Team, 2020, v.3.6.3). All variables were initially compared by a mixed-model ANOVA, where the fixed effect was stocking rate (hectare per steer) and the random effect was year using the "lmer" function of the "lme4" package (Bates et al., 2015). Least-squares means were then generated and, following the significance of the ANOVA, mean separation was done using linear, quadratic, and cubic polynomial contrasts using the "emmeans" package (Lenth, 2020).

Further analysis of the variables was done using linear mixed-model regression, where the highest polynomial order of stocking rate was explored depending on the significance of the polynomial contrasts. The regression models were done using the lmer function with year as a random effect. To illustrate goodness of fit, the approach of Nakagawa et al. (2017) was used. This approach determines the marginal-R^2, which is the proportion of variance explained by fixed effects only, and a conditional-R^2, which takes both the fixed and random effects into account. The marginal and conditional-R^2 values were determined using the "r2_nakagawa" function of the "performance" package (Lüdecke et al., 2020). The regression equations were plotted by first creating predicted points bounded within the stocking rates used in the current experiment. This was done so that when the response variable was plotted against stocking rate, the regression line plotted would be the one generated by the linear mixed model, and then plotting the resulting line was done by the "ggplot" function (Wickham, 2016). Results were considered significant at $P \leq 0.05$.

RESULTS

Carrying Capacity of Pastures

Over the 7-yr period, this research was conducted, the average precipitation during the growing season was 118% of the historical average (Table 1). Growing season precipitation ranged from a low of 57% of the historic average in 1994 (282 mm) to 160% of the historic average in 1995 (786 mm). All years in this experiment were at least 90% of the historic growing season average precipitation, with the exception of 1994.

Forage mass (kg dry matter [DM]/ha, Table 2) did not differ ($P = 0.64$) at the beginning of the grazing season in April. Thus, the mixed-model regression (Table 5) of forage mass in April was best explained ($R^2 = 0.63$) by the intercept (1,748 ± 166.7 kg/ha) alone. By July, forage mass declined by 17% from 2,014 kg/ha at 4.13 ha/steer to 1,661 at the 1.83 ha/steer stocking rate in a linear ($P < 0.01$) fashion with increasing stocking rate (i.e., decreasing hectares available per steer). Forage mass in July increased ($P < 0.01$) by 177.2 ± 49.4 kg/ha for each additional hectare available per steer ($R^2 = 0.59$, Table 5). In September, at the end of the grazing season, forage mass ($P < 0.01$) decreased with increasing stocking rate (decreased hectare/steer), for instance, forage mass decreased 21%

Table 1. Precipitation[a] and steer BW collection dates during the 1990 to 1996 period at the Marvin Klemme Range Research Station near Bessie, OK

Year	Growing season precipitation, mm	Starting date	Mid-point	Ending date	Total days
1990	489	April 25	July 26	September 16	144
1991	461	April 26	July 23	September 30	157
1992	668	April 15	July 22	September 27	165
1993	621	April 15	July 20	September 28	166
1994	282	April 4	July 7	September 7	154
1995	787	April 12	July 8	October 3	174
1996	753	April 3	July 10	September 24	174
7-yr mean	580	-	-	-	-
Long-term mean[b]	490	-	-	-	-

[a]Precipitation from the weather station located in Cordell, OK 6.4 km from the study site (iAIMS Climatic Data, 2020).
[b]Historical average from 1936 to 2010 (iAIMS Climatic Data, 2020).

from 2,004 kg/ha at 4.13 ha/steer and by 31% at 3.04 ha/steer to 1,579 at the 1.83 ha/steer stocking rate. Forage mass in September was explained (R^2 = 0.67, Table 5) by a cubic relationship with stocking rate (SR, hectare/steer), Forage mass kg/ha = 927.8 + 319.4 × SR^2 – 61.7 × SR^3.

Forage allowance (Table 2) at the initiation of the grazing season in April, at the mid-point of the summer grazing season in July, and at the end of the summer grazing season in September decreased ($P < 0.01$) as stocking rates increased (Table 2). In April and July, forage allowance was described by a linear relationship (R^2 = 0.85), where forage allowance (Table 5) increased ($P < 0.01$) by 8.9 and 7.1 kg forage DM/kg steer BW for each additional hectare/steer, respectively. While in September the relationship between forage allowance and stocking rate (Table 5) was described (R^2 = 0.87) by the cubic equation forage allowance = 3.81 × SR^2 – 0.58 × SR^3 – 1.18 ($P < 0.01$, R^2 = 0.57).

The actual forage demand imposed on the pastures as measured by AUD per hectare (Table 2) decreased in a cubic fashion as stocking rate increased, which was explained by grazing days, AUD/ha = 178.7 – 104.5 × SR + 26.4 × SR^2 – 2.4 × SR^3 ($P < 0.01$, R^2 = 0.99, Table 5) which is related to the design of the experiment and provided actual forage demands ranging from 27.7 AUD/ha at the lightest stocking rate (4.13 ha/steer) to 61.1 AUD/ha at the greatest stocking rate (1.83 ha/steer).

Steer Performance

The impact of stocking rate on BW and BW gain of steers grazing mid-grass prairie is presented in Table 3. Steer BW at the initiation of grazing was similar (P = 0.70), averaging 216 ± 4.9 kg, which provided for the initial targeted forage demand ranging from 22.5 to 50 AUD/ha based on the initial BW of the steers. In July, steer BW increased

Table 2. Least-squares means of forage and carrying capacity of mixed-grass prairie range units at a range of stocking rates (hectares per steer) from 1990 to 1996 at the Marvin Klemme Range Research Station near Bessie, OK

	Stocking rate, hectare/steer									Polynomial contrasts		
	1.83	1.91	2.29	2.76	3.04	3.61	4.13	SE	*P*-value	Linear	Quadratic	Cubic
Forage mass, kg dry matter/ha												
April	1,685	1,638	1,598	1,799	1,929	1,795	1,873	211	0.64	-	-	-
July	1,661	1,900	1,677	2,073	2,153	2,213	2,014	148	<0.01	<0.01	0.11	0.07
September	1,579	1,880	1,598	1,982	2,424	2,189	2,004	194	<0.01	<0.01	0.05	0.02
Forage allowance, kg forage dry matter/kg BW												
April	14.6	14.8	17.2	23.3	26.7	30.5	36.1	9.00	<0.01	<0.01	0.15	0.49
July	10.3	12.1	12.8	19.0	21.2	25.7	27.2	1.91	<0.01	<0.01	0.42	0.11
September	8.7	10.6	10.9	16.1	20.6	22.2	23.4	1.45	<0.01	<0.01	0.88	<0.01
Grazing days, AUD/ha[a]	61.1	58.6	48.9	40.8	36.9	32.5	27.7	2.17	<0.01	<0.01	<0.01	<0.01

[a]Animal unit equivalent days per hectare.

Table 3. Effect of stocking rate (hectares per steer) of mixed-grass prairie on performance of growing steers from 1990 to 1996 at the Marvin Klemme Range Research Station near Bessie, OK

	Stocking rate, hectare/steer									Polynomial contrasts		
	1.83	1.91	2.29	2.76	3.04	3.61	4.13	SE	*P*-value	Linear	Quadratic	Cubic
BW, kg												
April	214	215	216	216	216	216	217	4.9	0.70	-	-	-
July	300	302	302	306	307	313	309	9.6	<0.01	<0.01	0.64	0.30
September/October[a]	337	338	338	341	347	355	354	13.0	<0.01	<0.01	0.19	0.15
Average daily gain, kg												
Early summer	0.92	0.94	0.93	0.97	0.99	1.04	0.99	0.05	<0.01	<0.01	0.73	0.09
Late summer	0.53	0.51	0.52	0.51	0.58	0.62	0.65	0.10	<0.01	<0.01	< 0.01	0.39
Total season	0.75	0.75	0.75	0.77	0.81	0.86	0.84	0.04	<0.01	<0.01	0.14	0.07
BW gain/ha, kg	66.8	64.1	53.2	45.1	42.7	39.9	33.1	4.01	<0.01	<0.01	0.03	0.82

[a]Steers grazed from April 25 to September 16, 1990 (144 d); April 26 to September 30, 1991 (157 d); April 15 to September 27, 1992 (165 d); April 15 to September 28, 1993 (166 d); April 4 to September 7, 1994 (154 d); April 12 to October 3, 1995 (174 d); and April 3 to September 24, 1996 (174 d).

linearly ($P < 0.01$) with decreasing stocking rate (Table 3) with steer BW increasing 4.5 kg for each additional hectare available per steer ($P < 0.01$; $R^2 = 0.95$; Table 5). At the end of the grazing season, steer BW (Table 3) increased linearly with reduced stocking rate from 337 kg/steer at the highest stocking rate (1.83 ha/steer) to 354 kg/steer at the lightest stocking rate (4.13 ha/steer). Steer BW at the end of the grazing season was increased ($P < 0.01$; $R^2 = 0.97$) by 8.3 kg for each available hectare per steer (Table 5).

Average daily gains in the early summer decreased linearly ($P < 0.01$) with increasing stocking rate (Table 3) by 0.04 kg for each additional hectare available per steer ($R^2 = 0.85$; Table 5). Late season ADG decreased with increasing stocking rate from a high of 0.65 kg at 4.13 ha/steer stocking rate to 0.51 kg at the 1.91 ha/steer stocking rate. Late season ADG were explained ($P < 0.01$; $R^2 = 0.95$) by a quadratic function; ADG, kg = 0.5 + 0.01 × SR (ha/steer)^2. For the entire summer grazing season ADG decreased linearly ($P < 0.01$) with increasing stocking rate (Table 3) such that for each additional hectare per steer ADG increased by 0.05 kg ($R^2 = 0.88$; Table 5).

Body weight gain per hectare (Table 3) increased quadratically ($P < 0.01$) with increasing stocking rate, even though individual steer's ADG decreased as stocking rate increased which is described by BW gain/ha, kg = 132 – 46.1 × SR + 5.4 × SR^2 ($R^2 = 0.93$; Table 5). As the stocking rate increased from 4.13 ha/steer to 1.83 ha/steer, BW gain per hectare doubled from 33.1 kg/ha to 66.8 kg/ha, respectively (Table 3).

Economics of Stocking Rate

The effects of stocking rate on net returns per steer and net returns per hectare with and without the land rental cost of $27.17/ha (USD) are presented in Table 4. When land costs are included, net return per steer increased linearly ($P < 0.01$) from $52 (USD)/steer at the 4.13 ha/steer stocking rate to $95/steer for the 1.83 ha/steer stocking rate. With land costs included in the analysis, net return per hectare increased linearly ($P < 0.01$) from $13 (USD) at the 4.13 ha/steer stocking rate to $52/ha at the 1.83 ha/steer stocking rate. For each additional hectare available per steer, net return was reduced by $15.80 (USD)/steer and $15.70 (USD)/hectare (Table 5).

Removing land costs from the analysis changed the results for the net return per steer (Table 4). There was a cubic effect ($P = 0.05$) of stocking rate on net return per steer without land expense included with the highest net returns per steer at lower stocking rates and reductions in net return per steer with increasing stocking rate, which is explained by Net Return, $(USD)/steer = 492.00 – 400.00 × SR + 144.70 × SR^2 – 16.20 × SR^3 ($R^2 = 0.84$; Table 5). Even though net returns per steer were greater at lighter stocking rates when land cost was not included in the analysis, net return per hectare linearly increased ($P < 0.01$) from $40/ha at the 4.13 ha/steer stocking rate to $79/ha at the 1.83 ha/steer stocking rate (Table 4). For each additional hectare available per steer, net returns decreased by $15.60 (USD)/hectare ($R^2 = 0.84$; Table 5).

Table 4. Effect of stocking rate (hectares per steer) of growing steers grazing mixed-grass native prairie pastures[a] from 1990 to 1996 at the Marvin Klemme Range Research Station near Bessie, Oklahoma on economics[b] of the stocker cattle enterprise with and without a land rental cost[c]

	Stocking rate, hectare/steer									Polynomial Contrasts		
Item	1.83	1.91	2.29	2.76	3.04	3.61	4.13	SE	*P*-value	Linear	Quadratic	Cubic
With Land Cost												
Net return, $/steer[d]	95	91	79	71	76	73	52	11.8	< 0.01	< 0.01	0.69	0.1
Net return, $/ha[d]	52	47	35	26	24	22	13	5.2	< 0.01	< 0.01	0.08	0.54
Without Land Cost												
Net return, $/steer[d]	144	143	142	146	158	171	164	11.8	< 0.01	< 0.01	0.19	0.05
Net return, $/ha[d]	79	74	62	53	52	49	40	5.2	< 0.01	< 0.01	0.07	0.51

[a]Steers grazed from April 25 to September 16, 1990 (144 d); April 26 to September 30, 1991 (157 d); April 15 to September 27, 1992 (165 d); April 15 to September 28, 1993 (166 d); April 4 to September 7, 1994 (154 d); April 12 to October 3, 1995 (174 d); and April 3 to September 24, 1996 (174 d).

[b]Based on the 10-yr average prices for Oklahoma livestock markets from 2009 to 2018 with purchase of 205 kg steers in March and sales of 340 kg steers in October (USDA, 2020) and the inputs used during the experiment.

[c]Annual land cost was set at $ (USD) 27.17/ha, based on rental rates published by the USDA NASS (2015).

[d]U.S. dollars.

Table 5. The final mixed-model regression equations

	Fixed effects[b]								R^2	
Item[a]	Intercept	SE	Linear	SE	Quadratic	SE	Cubic	SE	Marginal[c]	Conditional[d]
Forage mass										
April	1,748.5**	166.7							0.04	0.63
July	1,453.0**	181.7	177.2**	49.4					0.12	0.59
September	927.8**	311.2	NS	—	319.4**	99.6	−61.7**	21.3	0.14	0.67
Forage allowance										
April	−3.34	3.43	8.93**	0.62					0.59	0.85
July	−3.24	2.22	7.11**	0.41					0.62	0.84
September	−1.18	2.33	NS	—	3.81**	0.40	−0.58**	0.09	0.68	0.87
Grazing days, AUD/ha	178.7**	19.4	−104.5**	21.3	26.4**	7.5	−2.4**	0.8	0.83	0.99
BW										
Initial	215.9**	4.8							<0.01	0.96
Mid-summer	292.9**	9.8	4.5**	1.0					0.02	0.95
Ending	320.9**	13.0	8.3**	1.2					0.04	0.97
Average daily gain										
Early summer	0.9**	0.06	0.04**	0.01					0.05	0.85
Late summer	0.5**	0.10	NS	—	0.01**	0.002			0.03	0.95
Total season	0.66**	0.04	0.05**	0.01					0.11	0.88
Gain per hectare	132.0**	9.9	−46.1**	6.7	5.4**	1.1			0.58	0.93
Net return with land cost										
Per steer	120.2**	12.1	−15.8**	2.3					0.16	0.85
Per hectare	74.9**	5.6	−15.7**	1.4					0.49	0.84
Net return without land cost										
Per steer	492.0**	146.3	−400.0*	160.9	144.7*	56.6	−16.2*	6.4	0.11	0.86
Per hectare	101.8**	5.6	−15.6**	1.4					0.49	0.84

The models implemented linear, quadratic, and cubic effects of stocking rate (hectares/steer) across the dependent variables. Model terms were only included in the regression when they were found to be significantly ($P < 0.05$) different from zero.

[a]The dependent variables were forage mass, kg forage dry matter (DM)/ha; forage allowance, kg forage DM/kg steer BW; BW, steer BW, kg; average daily gain (ADG), kg/d; net return with land cost, net return in USD on per steer or per hectare basis including a $ (USD) 27.17/ha land rental cost; Net return without land cost, net return in USD on per steer or per hectare basis without cost of land included in the analysis.

[b]The regression analysis explores the effects of stocking rate, with linear, quadratic, and cubic terms, on the dependent variables. Cubic, quadratic, and linear fixed effects were explored depending on the significance of the corresponding polynomial contrasts.

[c]Proportion of the variance of each dependent variable explained by the fixed effect of treatment only.

[d]The proportion of the variance which was not explained by the fixed effects but was explained by the random effect (year) is also reported, with the remainder of the variance being the residual standard deviation.

*Indicates significance at $0.01 < P \le 0.05$ and **indicates $P \le 0.05$. In the event that a higher order term was significant but a lower order term was not, NS was used to specify nonsignificant in the place of the coefficient.

DISCUSSION

The enterprise services that the stocker-cattle segment supplies to the beef industry are well characterized. These services include providing the market with immunocompetent weaned feeder cattle that have been acclimatized to feed bunks and water sources and have been grouped in lot sizes appropriate to the United States beef industry. Other services include providing placement area for calf numbers that are in excess of feedyard capacity at times of the year when large numbers of calves are marketed (Troxel and Barham, 2012). As the cost of BW gains during finishing has increased 85% from 2000 to 2011 (Waggoner, 2020), the value of BW gain (USDA, 2020) for stocker calves increased by 134% from the annual average value of BW gain of approximately $50/45.4 kg in 1990 to 2000 to $111/45.4 kg in 2011, indicating an increase in the profit potential of stocker programs. Even though the margins on BW gain have increased, there have also been increases in the costs of fertilizer, fuel, and land; putting a cost-price squeeze on producers, giving them the perception that maximizing production is required to stay solvent, which could be potentially harmful to pasture and rangeland conditions and crippling the long-term sustainability of grazing enterprises.

Stocking rate is a fundamental variable for managing pastures and there is a distinct relationship between stocking rate and animal performance for each forage type (Bransby et al., 1988). The carrying capacity of a given rangeland unit refers to the maximum stocking rate over time that does not negatively impact vegetation resources (Holechek et al., 1998). Stocking rate is one of the few factors that producers have absolute control over with large impacts not only on animal production potential but also on short- and long-term forage production. Thus, stocking rate impacts not only the short- and long-term economics of the livestock grazing enterprise but also range condition, long-term sustainability, and associated ecosystem services. The desire to maintain future herbage production is significant to producers utilizing native rangeland, especially since heavier stocking rates have been shown to decrease future herbage production potential in western Oklahoma (Adiku et al., 2010). Maintaining adequate residual herbage mass on native rangelands not only protects the landscape from both water and wind erosion, but also provides escape cover for wildlife, improves water infiltration, and sustains herbage production potential for following years (Khumalo and Holechek, 2005; Adiku et al., 2010; Thacker et al., 2012; Wine et al., 2012; Freese et al., 2013).

The central tenant of grazing management is to control the frequency and intensity of consumption of desired plants (Heitschmidt and Walker, 1996). In rangelands composed of perennial native forages, this is primarily accomplished through setting stocking rates by grazing livestock densities that achieve light to moderate forage utilization (25% to 50%) (SCS, 1960). Stocking rate has more influence on vegetation productivity than other management factors (Holechek et al., 1998; Adiku et al., 2010) and a moderate stocking rate can lead to more rapid rangeland improvements than a light stocking rate or complete protection from grazing (Holechek et al., 1998; Gillen and Sims, 2006). Thus, a moderate stocking rate is more likely to provide additional ecosystem services than an ungrazed or lightly grazed rangeland since large grazing ungulates are an inherent part of the ecosystem, whether they are of wild or domestic origin.

The lack of difference in forage mass at the beginning of the grazing season in April indicates there was no carry-over effect from the stocking rates of the previous grazing season because stocking rates were maintained in the same pastures every year. Reductions in forage mass in the mid-summer indicate that forage utilization was increased by 17% at the highest stocking rate (Table 2). Using calculations based on the first derivative of the cubic equation from the end of the grazing season in September, forage mass was maximized at 2,195 kg/ha with a stocking rate of 3.45 ha/steer, thus based on this and the ending forage mass at the highest stocking rate (1,579 kg/ha) forage utilization was 28% higher at the highest stocking rate. The stocking rates used in this experiment ranged from near the USDA SCS (1960) recommended stocking rate of 25 AUD/ha (27.7 AUD/ha, Table 2) to 2.2 times the recommended stocking rate at 61.1 AUD/ha. The USDA SCS (1960) recommended stocking rate is generally considered to be light stocking (25% utilization of forage production), so the highest stocking rate is estimated to utilize over 50% of forage production which is considered a heavy grazing intensity (Heitschmidt et al., 1990). These reductions in total forage mass with increasing stocking rate are similar to what was reported by Gillen et al. (2000), who reported reductions in total standing crop and dead standing crop with

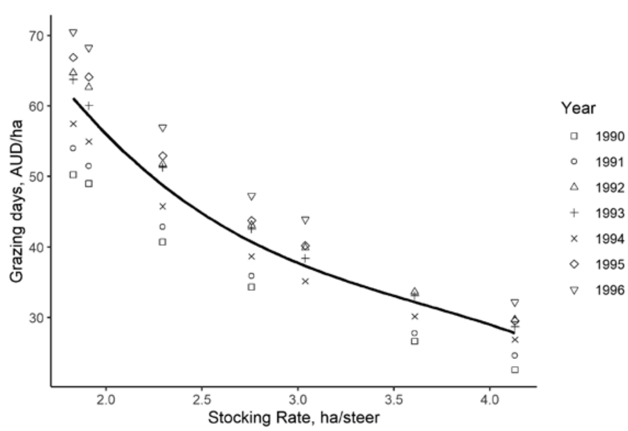

Figure 1. Animal unit days (AUD)/ha for stocking rates across years. The black line is the regression equation fit by linear mixed model using year as a random effect and linear, quadratic, and cubic terms of stocking rate as fixed effects.

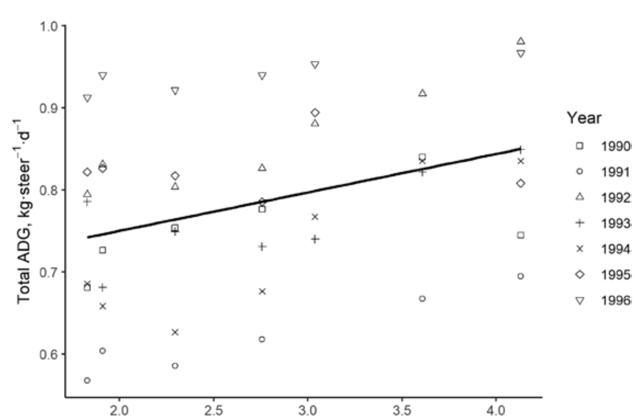

Figure 2. Average daily gain (kg) increased with a lighter stocking rate (i.e., increasing area allocated per steer). The black line is the regression equation fit by linear mixed model using year as a random effect and the linear effect of stocking rate as fixed effects. For every additional hectare allocated per steer, there was a 0.05 kg increase in average daily gain.

increasing stocking rate, but no difference in live standing crop for the July and September sampling dates. Using higher stocking rates during times of drought is even more detrimental to animal performance than conservative stocking rates and increase the risk to producers because of the greater financial losses reported to the cattle enterprise (Klipple and Costello, 1960; Shoop and McIlvain, 1971; Torell et al., 2010). As previously stated, the desire to maintain future herbage production is significant to producers using native rangeland because heavier stocking rates can decrease future herbage production (Adiku et al., 2010) as a result of damage to plant roots (Pulido et al., 2017) and a decrease in water infiltration (Rhoades et al., 1964; Ahmed et al., 1987) resulting from soil compaction.

Forage allowance is a measure of the relationship between forage availability and the number of animal units on a pasture at a given point in time competing for an optimal diet (Allen et al., 2011a, b). This measure describes the potential grazing selectivity of grazing livestock and has been tied closely to potential animal performance (Beck et al., 2013; Rouquette, 2016; Rouquette, 2017). The critical point where forage allowance maximizes animal performance differs for differing types of forage resources (Rouquette, 2016) and is different for similar forages under differing seasons or growing conditions (Beck et al., 2013; Rouquette, 2016). The forage allowance in September was calculated to be maximized at 23.3 kg forage DM/kg steer BW with a stocking rate of 4.38 ha/steer.

The recommended sustainable stocking rate for this site was 25 AUD/ha based on USDA

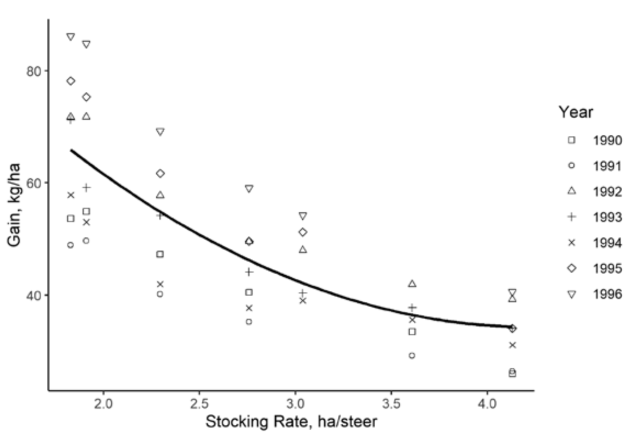

Figure 3. Body weight gain (kg) per hectare over the grazing season decreased with a lighter stocking rate (i.e., increasing area allocated per steer). The black line is the regression equation fit by linear mixed model using year as a random effect and the linear and quadratic effect of stocking rate as fixed effects. The predicted vertex of the quadratic equation was determined to be at 4.24 hectare per steer, indicating that as area per steer was increased, steer gain per hectare was reduced until the stocking rate of 4.24 ha per steer, where a plateau occurs.

Soil Conservation Service estimates (SCS, 1960). In the current experiment, AUD was calculated based on the average BW of the steers over the entire grazing season and the days spent grazing each season, while the AUD/ha used in the Gillen et al. (2000) analysis was based on the initial BW of steers and the grazing days each season. Steers would be expected to grow through the summer grazing season resulting in an increased herbage demand (Vallentine, 1989; NASEM, 2016). Hence, the growth of the cattle would increase the stocking rate and would be expected to decrease the rate of BW gains by calves, and thus the AUD was calculated as a response variable to stocking rate for each pasture each year based on this premise. Figure 1 shows the response surface of the effects of stocking rate on AUD/hectare, as would be expected the maximum of 61 AUD/ha was observed at the heaviest stocking rate (1.83 ha/steer) and the lowest AUD/ha of 27 AUD/ha was observed at the lightest stocking rate of 4.13 ha/steer.

The early summer ADG increased 0.04 kg/d with each additional hectare available per steer, along with the increases in forage mass and forage allowance, which would provide more selectivity of grazing (Beck et al., 2013; Rouquette, 2016; Rouquette, 2017). In the late summer, the intercept for ADG was less than in the early summer (0.5 kg/d vs. 0.9 kg/d; Table 5) likely due to seasonal reductions in forage quality (Gunter et al., 1995). Reduced forage mass and forage allowance with increasing stocking rate, which would be related to reduced selectivity of grazing, decreased late summer ADG by 0.12 kg/d, from 0.65 kg/d at the lightest stocking rate to 0.53 kg/d at the heaviest stocking rate. The decreases in forage allowance throughout the summer grazing season were related to reductions in ADG both in the early summer and late summer, but the reductions in forage allowance appeared to restrict performance to a greater extent during the late summer, when enhanced selectivity of the overall lower quality forage (Gunter et al., 1995) appears to be of greater benefit. Over the entire summer grazing season, steer ADG is predicted to reach a minimum of 0.75 kg/d at the stocking rate of 1.83 ha/steer and were maximized at 0.86 kg/d with the 4.13 ha/steer stocking rate but did not reach nadirs of either minimum or maximum production (Figure 2). These findings could also be applied to future climatic conditions. Elevations in CO_2 and temperatures associated with global climate change are expected to increase forage production of mixed-grass prairies by 38%, but reduce both

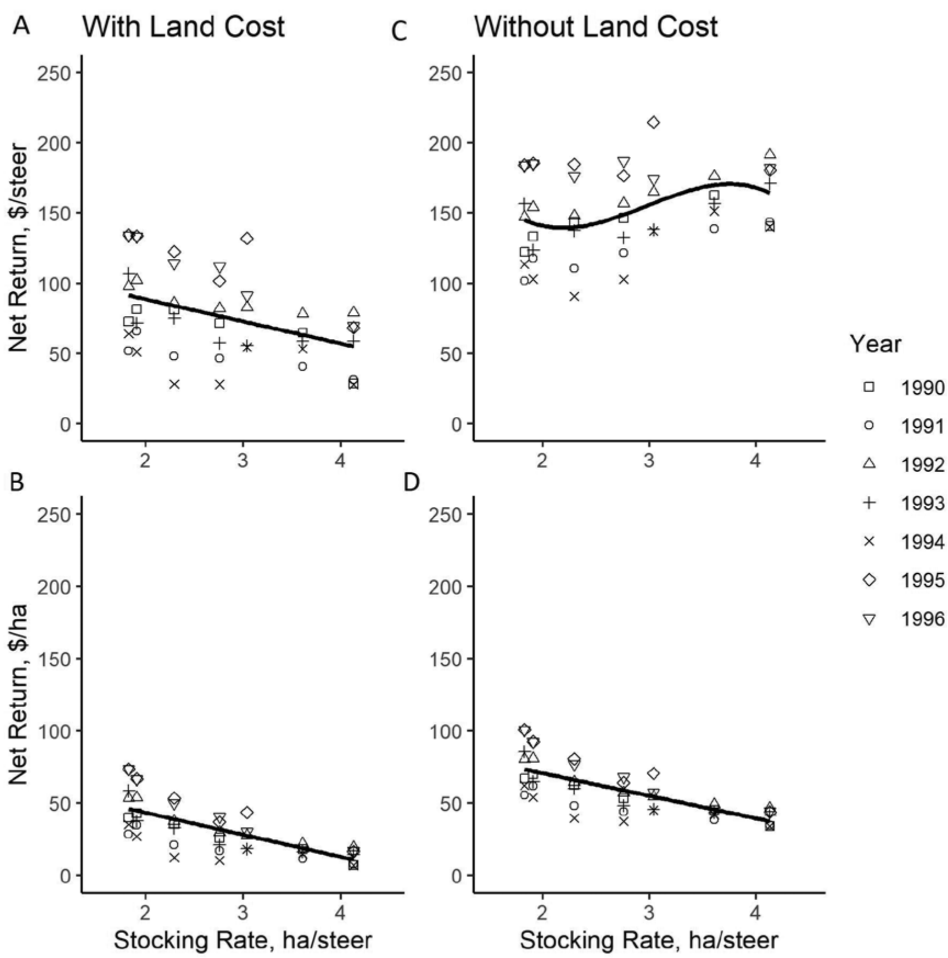

Figure 4. Net return (NR) over the grazing season at different stocking rates. The black line is the regression equation fit by a linear mixed model using year as a random effect. The points are observations each year for each stocking rate. Net return [both in $/steer (panel A) and $/ha (panel B)] decreased linearly when a fixed cost was attributed to land. When a fixed cost was not attributed to land, NR per steer (panel C) exhibited a cubic relationship, where NR ($/steer) increased at the lightest stocking rates, whereas NR per hectare decreased linearly with lighter stocking rates (panel D).

forage crude protein and digestibility (Augustine et al., 2018), thus setting stocking rates to optimize forage allowance and diet selectivity may become even more critical in the future.

Body weight gain per hectare is an economically important metric for production. As BW gain per hectare increases, the costs per production unit (land area) are spread over more kg of BW, thereby reducing the cost per kg of BW. Figure 3 shows the response surface for the reaction of BW gain per hectare to changes in stocking rate. The current research did not reach an inflection point where BW gain per hectare reached a maximum and began to decline. However, some research has indicated that this occurs following a critical stocking rate (Riewe et al., 1961; Holechek et al., 1998; Gunter et al., 2005) depending on the conditions during the experimental period.

When an annual cost of land of $27.17/ha was imposed on the stocker cattle enterprise, net returns per steer increased with increasing stocking rates (Table 4) even though performance and BW per individual at marketing (Table 3) was decreased. This was due to the reduced land expense of fewer hectares being charged against each steer (Figure 4A). Net return per hectare with the land rental expense charged against the stocker cattle enterprise likewise did not reach a maximum or minimum within the bounds of the stocking rates used in the present experiment and within the range of the data were greatest at the highest stocking rate of 1.83 ha/steer (Figure 4B).

The response surface for changes in net return per steer with changes in stocking rate is presented in Figure 4C. When the land expense was not charged against the stocker enterprise net returns per steer increased with greatest net return per steer of $172.57 (USD)/steer at a stocking rate of 3.77 ha/steer and were lowest at $139.84 (USD)/steer at a stocking rate of 2.18 ha/steer. Net return per hectare without land rental expense did not reach a plateau within the confines of the stocking rates used in the current experiment, and within the range of the data were maximized at the highest stocking rate of 1.83 ha/steer (Figure 4D).

Characteristically, the greatest net returns are believed to be found at stocking rates between the points of greatest individual animal performance and the greatest BW production per hectare (Frasier and Steffens, 2013), but this experiment was not able to capture the greatest production per hectare within the bounds of the stocking rates used. In a 6-yr study conducted with moderate or heavy season-long stocking rates and grazing management in a growing steer system in Wyoming, Hart et al. (1988) found the economically optimal stocking rate to be 60% to 80% greater than the SCS recommended stocking rate, depending on the economic conditions encountered, but the authors cast doubts on the ability of range conditions to withstand long-term use at these levels. Even though stocking rates were increased dramatically in this experiment compared with SCS recommendations, Gillen et al. (2000) reported little response in vegetation species composition over the course of this 7-yr experiment, indicating that stocking rates at this site may have been supported by the favorable weather conditions during the experiment or that the site was in equilibrium with the historic continuous heavy utilization. Sims and Gillen (1999) reported on a stocking intensity experiment conducted on mixed-grass prairie from 1941 to 1951 with steers grazing year-round at 41, 53, and 82 AUD/ha. In this experiment, basal cover increased from 5% in 1941 to 15% in 1951 across all treatments, which indicated recovery from previous heavy use and drought. As with the current experiment, BW gain per steer decreased with increasing stocking rate while BW gain and net returns per unit land area increased, leading the authors (Sims and Gillen, 1999) to conclude that during periods of extended favorable rainfall conditions the carrying capacity of this mixed-grass prairie site may reach over 82 AUD/ha.

It is well known that the optimal stocking rate is bounded by the stocking rate that generates the maximum animal performance and the stocking rate that maximizes production per unit of land area. Because of the variable costs associated with animal management, the most profitable stocking rate is less than the stocking rate with the greatest production per hectare and overhead costs do not influence the economically optimal stocking rate, but overhead costs do affect net returns (Frasier and Steffens, 2013). When only short-term profitability is emphasized, the long-term impacts of today's stocking rate decisions can influence sustainability by degrading future rangeland productivity and ecosystem services (Shoop and McIlvain, 1971; Steiner et al., 2019) along with consumer perceptions of the impacts of livestock production on the ecosystem services provided by rangelands (Leroy et al., 2018).

Under the favorable climatic conditions of this 7-yr experiment, economically optimal stocking rates can be more than doubled compared with the stocking rate recommended by the USDA Soil Conservation Service. Increasing stocking rates decreased individual animal performance but did not reach a point of maximum BW gain per unit of land area, which leads to the increasing economic returns observed. The highest stocking rates did not affect measures of rangeland condition reported by (Gillen et al., 2000), but the time period of this experiment may not have been adequate to effectively capture changes in rangeland vegetation cycles through pluvial and arid periods. More research is needed to determine the long-term implications of these stocking rates during arid conditions and setting stocking rates based on seasonal weather patterns and extended weather outlook predictions.

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