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Temperature and Precipitation Affect Steer Weight Gains Differentially by Stocking Rate in Northern Mixed-Grass Prairie

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Abstract

Cattle weight gain responses to seasonal weather variability are difficult to predict for rangelands because few long-term (>20 yr) studies have been conducted. However, an increased understanding of temperature and precipitation influences on cattle weight gains is needed to optimize stocking rates and reduce enterprise risk associated with climatic variability. Yearling steer weight gain data collected at the USDA-ARS High Plains Grasslands Research Station at light, moderate, and heavy stocking rates for 30 years (1982–2011) were used to examine the effects of spring (April–June) and summer (July–September) temperature and precipitation, as well as prior-growing-season (prior April–September) and fall/winter (October–March) precipitation, on beef production ($\text{kg} \cdot \text{ha}^{-1}$). At heavier stocking rates, steer production was more sensitive to seasonal weather variations. A novel finding was that temperature (relatively cool springs and warm summers) played a large predictive role on beef production. At heavier stocking rates, beef production was highest during years with cool, wet springs and warm, wet summers, corresponding to optimum growth conditions for this mixed C_3–C_4 plant community. The novelty and utility of these findings may increase the efficacy of stocking rate decision support tools. The parsimonious model structure presented here includes three-month seasonal clusters that are forecasted and freely available from the US National Oceanic and Atmospheric Administration up to a year in advance. These seasonal weather forecasts can provide ranchers with an increased predictive capacity to adjust stocking rates (in advance of the grazing season) according to predicted seasonal weather conditions, thereby reducing enterprise risk.

Key Words: beef cattle production, climate variability, decision support tools, grazing management, model averaging, semiarid rangeland

INTRODUCTION

Much has been ascertained over the last six decades regarding rangeland management practices and beef production (Holechek et al. 1998; Briske et al. 2011), but understanding the influence of climatic variables such as temperature and precipitation on cattle weight gains remains problematic. There are few long-term studies undertaken in resource management (Lindenmayer et al. 2012) and beef production (Briske et al. 2011), although such studies are invaluable. Of the few studies that have addressed long-term cattle weight gains (e.g., Willms et al. 1986; Hart and Ashby 1998; Derner et al. 2008), only Derner et al. (2008) examined the influence of precipitation on cattle weight gains, finding that higher spring (April–June) precipitation totals increased beef production in northern mixed-grass prairie. Further elucidating the effects of precipitation (and temperature) on beef production would assist in modeling efforts to help ranchers maximize production and minimize enterprise risk (Derner et al. 2012).

Previous modeling efforts have examined the effects that climate change may have either directly or indirectly on beef production (e.g., Hanson et al. 1993; Andales et al. 2005; Mader et al. 2009; Ritten et al. 2010; Torell et al. 2010). These models, however, were not founded on data that originally and directly linked long-term cattle weight gains to corresponding climatic variability. Climatic variability and timing of precipitation influences productivity of grasslands (Craine et al. 2012), as well as bison weight gains in tallgrass prairie (Craine et al. 2009). Inclusion of relationships between climatic variability and beef production from long-term data would increase the accuracy and reliability of predicted cattle weight gains. Given that temperature and precipitation data, as well as forecasts, can easily be gathered from multiple sources such as the US National Oceanic and Atmospheric Administration (NOAA),[1] models including the effects of temperature and precipitation on beef production would have more utility for livestock producers. Accordingly, a direct linkage between seasonal weather variability and cattle weight gains was the primary relationship explored here.

Data on yearling steer weight gains, along with temperature and precipitation, have been collected at the USDA-ARS High

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[1] http://www.noaa.gov

Plains Grasslands Research Station (HPGRS) near Cheyenne, Wyoming, USA (see site description below) since 1982. Prior analyses have been performed on subsets of these data (Hart et al. 1988; Manley et al. 1997; Derner et al. 2008). Stocking rate and spring precipitation influence cattle weight gains in this northern mixed-grass prairie (Derner et al. 2008). We expand on these prior studies by examining data covering the entire 30-yr period (1982–2011), with hypotheses that 1) greater spring (April–June) and summer (July–September) precipitation will increase beef production, with temperature having a smaller or negligible effect, and 2) sensitivity to climate variables will be most pronounced at heavy stocking rates, with decreasing sensitivity for moderate and light stocking rates.

METHODS

Site Description

This experiment began in 1982 on northern mixed-grass prairie at HPGRS (~7 km northwest of Cheyenne, Wyoming, USA; lat 41°11′N, long 104°53′W). The primary ecological site is Loamy (Site ID is R067AY122WY). Mean annual precipitation (132 yr) is 381 mm, peaking in May. Soils at HPGRS are well-drained and coarse, and largely comprised of Albinas, Ascalon, and Altvan loams (mixed mesic Aridic Argiustolls), and Cascajo gravelly loam (mixed mesic Aridic Calciorthid) (Stevenson et al. 1984). Vegetation is predominately grasses. Perennial cool-season (C_3) graminoids include western wheatgrass (*Pascopyrum smithii* [Rydb.] Á. Löve), needle-and-thread (*Hesperostipa comata* [Trin. & Rupr.] Barkworth), prairie junegrass (*Koeleria macrantha* [Ledeb.] J.A. Schultes), and needleleaf sedge (*Carex duriuscula* C.A. Mey). Blue grama (*Bouteloua gracilis* [H.B.K.] Lag. ex Griffiths) is the primary perennial warm-season (C_4) grass. Scarlet globemallow (*Sphaeralcea coccinea* [Nutt.] Rydb.) is the primary forb, and fringed sage (*Artemisia frigida* Willd.) is the primary subshrub. Warm-season grasses and forbs increase, while cool-season grasses decrease, under heavy stocking rates (Manley et al. 1997).

Grazing Treatments

Three season-long (early June–early October), continuous grazing treatments were initiated in 1982 on two replicate pastures per treatment (data combined from replicates for analyses described below; light stocking rate not replicated) and have continued each year to the present: light (15.7 ± 2.8 animal unit days per hectare [$\mathrm{AUD} \cdot \mathrm{ha}^{-1}$]; mean ± SD), moderate (32.6 ± 5.5 $\mathrm{AUD} \cdot \mathrm{ha}^{-1}$), and heavy ($43.4 \pm 7.3$ $\mathrm{AUD} \cdot \mathrm{ha}^{-1}$) stocking rates (Table 1). These stocking rates were originally established to be ~35% below, equal to, and ~33% above USDA-NRCS recommended stocking rates respectively (Hart et al. 1988). Yearling steers (Hereford, Black Angus, or crossed English breeds) were used as grazing animals, and each steer was weighed before and after each grazing season. Prior to each weighing, steers were held overnight without food or water. All experimental procedures were undertaken with HPGRS Animal Care and Use Committee oversight. Total beef production per hectare ($\mathrm{kg} \cdot \mathrm{ha}^{-1}$) was calculated by dividing the sum of the seasonal gains for each steer in each treatment by the number of total hectares for that treatment. Cattle did not graze pastures in 1989, 2000, and 2002 because of severe droughts. Likewise, in 1994 and 2006, grazing seasons were shortened due to drought. See Table 1 for specific dates and stocking rates for each grazing season. An animal unit equivalent of 0.75 was used for the yearling steers in calculating the stocking rates (Holechek et al. 1998).

Statistical Analyses and Model Fitting

To test for effects both within-season and on the seasonal lag of temperature and precipitation on steer weight gains, model averaging methodology was used in JMP 10.0.0,[2] which averages models with respect to corrected Akaike Information Criterion (AICc) weights (SAS Institute Inc. 2012). Model averaging was used because it enabled the fitting and averaging of multiple competing models. Averaging across a set of models accounts for model uncertainty and selection procedure bias, ensuring a poor model was not selected (Wang et al. 2009). Model averaging results in models with excellent predictive abilities (SAS Institute Inc. 2012), and may always be more accurately predictive than "best-model" strategies (Burnham and Anderson 2004). Burnham and Anderson (2004) and Wang et al. (2009) provide reviews of model averaging.

In our model averaging structure, we used a maximum of eight terms because our models had eight total variables (see below). For the selection of models to be averaged, an AICc cutoff weight of 0.95 was used. For each variable, this model averaging methodology produces averaged (weighted) regression coefficients and corresponding standard errors (which indicate the bias of each coefficient toward zero). Resulting averaged variable coefficients were therefore considered robust (important) if they were larger than their respective standard errors. Because model averaging is an information-theoretic approach, trends must be interpreted and inferred from results tables, which can provide benefits over traditional null hypothesis testing and interpretation of *P*-values (Anderson et al. 2000).

We selected our model structure based on parsimony and a priori hypotheses (rather than "data dredging") to avoid spurious effects and overfitting of the data (Anderson et al. 2001). Our model structure was also selected to concur with weather predictions available to ranchers to maximize utility for decision support tools (Derner et al. 2012). For example, NOAA provides monthly outlooks for temperature and precipitation one month in advance, along with providing seasonal (three-month) outlooks up to a year in advance.[3] Our models used three-month clusters (see below), not only to be in line with available NOAA predictions, but also to provide biological meaning, as total spring (April–June) precipitation influences both beef production (Derner et al. 2008) and forage production (Derner and Hart 2007) in this system. Likewise, summer (July–September) precipitation could also clearly impact forage production, and because cattle grazing ended in late September or early October each year (Table 1), ending the summer cluster in September made this value biologically meaningful.

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[2] http://www.jmp.com/support/help/The_Model_Averaging_Option.shtml

[3] http://www.nws.noaa.gov/predictions.php

Table 1. Yearly grazing dates and stocking rates for light (L), moderate (M), and heavy (H) stocking treatments at High Plains Grasslands Research Station. Steers were not grazed in 1989, 2000, or 2002 because of drought. Seasons were shortened in 1994 and 2006 due to drought. Stocking rate (AUD · ha^{-1}) was calculated using days of grazing, total number of steers in pasture, and an animal unit equivalent of 0.75. Not all steers were used as study animals for determining beef production.

	Grazing period			No. of steers in pasture			Stocking rate (AUD · ha^{-1})		
Year	Start	End	Days	L	M	H	L	M	H
1982	24 June	19 October	117	11	8	8	11.8	29.3	39.0
1983	16 June	27 October	133	16	8	8	19.5	33.2	44.3
1984	12 June	2 October	112	18	8	8	18.4	28.0	37.3
1985	12 June	2 October	112	15	10	10	15.4	35.0	46.7
1986	10 June	8 October	120	15	10	10	16.5	37.5	50.0
1987	3 June	22 October	141	15	10	10	19.4	44.1	58.7
1988	23 June	12 October	111	15	10	10	15.2	34.7	46.3
1990	21 June	10 October	111	14	10	10	14.2	34.7	46.3
1991	18 June	23 October	127	19	10	10	22.1	39.7	52.9
1992	16 June	1 October	107	13	10	10	12.7	33.4	44.6
1993	6 June	30 September	116	14	10	10	14.9	36.2	48.3
1994	1 June	9 August	70	15	10	10	9.6	21.9	29.1
1995	21 June	12 October	113	15	10	10	15.5	35.3	47.1
1996	6 June	26 September	112	15	10	10	15.4	35.0	46.7
1997	4 June	24 September	112	14	10	10	14.3	35.0	46.7
1998	10 June	30 September	112	15	10	10	15.4	35.0	46.7
1999	10 June	17 October	129	15	10	10	17.7	40.3	53.8
2001	6 June	12 October	128	13	8	8	15.2	32.0	42.7
2003	9 June	17 October	130	15	8	8	17.8	32.5	43.3
2004	9 June	15 October	128	15	8	8	17.6	32.0	42.7
2005	7 June	14 October	129	15	8	8	17.7	32.3	43.0
2006	7 June	25 August	79	15	8	8	10.8	19.7	26.3
2007	6 June	12 October	128	15	8	8	17.6	32.0	42.7
2008	4 June	10 October	128	15	8	8	17.6	32.0	42.7
2009	4 June	30 September	118	15	8	8	16.2	29.5	39.3
2010	8 June	17 September	101	15	8	8	13.9	25.2	33.7
2011	6 June	8 September	94	15	8	8	12.9	23.5	31.3
Mean	—	—	115	—	—	—	15.7	32.6	43.4
SD	—	—	15.9	—	—	—	2.8	5.5	7.3

Our model had eight total variables (Table 2). For current spring (April–June) and summer (July–September) monthly clusters, we included total precipitation (mm), average (of the average) temperature (°C; the average of the midpoint between the maximum and minimum temperatures at HPGRS weather stations), and an interaction term of precipitation * temperature as predictors in the models. These two-way interaction terms were included in case the effects of temperature and precipitation alone were not additive. Finally, because prior-season precipitation can affect current-year forage production (Oesterheld et al. 2001), we also included prior growing season (April–September) and prior fall/winter (October–March) precipitation but not temperature.

We modeled total beef production (kg · ha^{-1}) separately for each of the three stocking rates (light, moderate, and heavy) to compare the effect sizes between stocking rates. This method allowed us to directly test our hypotheses (Anderson et al. 2001). It was also selected because initial models treating stocking rate as a continuous or categorical variable produced few interpretable patterns, due to the fact that stocking rate was such a strong predictor by itself that it overwhelmed and diminished climatic effects. Examinations of the effects of stocking rate alone on beef production were still performed for comparisons to prior studies, however. Models were constructed to maximize both biological meaning and management tool utility (Derner et al. 2012), rather than to build a complicated, intricate ecological model that might provide the best fit. Though a seemingly unlimited number of alternate model structures could have been constructed, our model structure was justifiable given the aims of this study.

RESULTS

Across study years (excluding 1989, 2000, and 2002, when steers were not grazed), considerable variability existed in the precipitation and temperature variables (Table 3). Prior April–September precipitation exhibited a four-fold range from 120.0 mm (2003) to 506.8 mm (1996), whereas prior October–March precipitation differed six-fold from 28.2 mm (2007) to

Table 2. Model averaged estimates for total beef production (kg · ha^{-1}). Sample sizes (*n*) reported in stocking rate column headings represent the number of models averaged (out of 255 possible) using a cutoff AICc weight of 0.95. Note that reported coefficients are not standardized, as results are to be used for predictive purposes and comparison to other data sets.

	Stocking rate					
	Heavy ($n = 120$)		Moderate ($n = 151$)		Light ($n = 81$)	
Variable	Estimate	SE	Estimate	SE	Estimate	SE
Intercept	57.767	—	42.734	—	20.275	—
April–June precipitation	0.016	0.016	0.025	0.014	0.001	0.003
April–June mean temperature	–3.836	1.172	–0.742	0.594	–0.158	0.196
(April–June precipitation) * (April–June mean temperature)	0.007	0.008	0.010	0.007	0.001	0.002
July–September precipitation	0.017	0.017	0.014	0.013	0.000	0.003
July–September mean temperature	1.667	0.902	0.096	0.354	–0.003	0.125
(July–September precipitation) * (July–September mean temperature)	0.004	0.010	0.003	0.007	0.000	0.003
Prior April–September precipitation	–0.013	0.011	–0.004	0.006	–0.015	0.005
Prior October–March precipitation	–0.015	0.020	–0.012	0.015	–0.007	0.007
Coefficient of determination (R^2)	0.58		0.46		0.42	

190.8 mm (1990). Spring (April–June) precipitation ranged from 71.4 mm in 2006 to 342.0 mm in 1983, with the average temperature ranging from 7.2°C in 1983 to 13.1°C in 1994. Summer (July–September) precipitation was lowest in 1998 with 53.6 mm and highest in 1997 with 263.7 mm, and the average temperature during this period ranged from 12.6°C in 2003 to 19.8°C in 1995.

Beef production increased with stocking rate (Fig. 1), whether considered as a continuous or qualitative variable (Figs. 1A and 1B, respectively). The spread of data points around the best fit line in Figure 1A increased with the stocking rate, and the largest standard error was associated with the heavy stocking rate in Figure 1B. Similarly, R^2 values and parameter estimates decreased as the stocking rate declined from heavy to moderate and light levels, with the exception being a slight increase in effect size for spring precipitation from the heavy to moderate stocking rate (Table 2). These higher amounts of data variability with increased stocking rate in Figure 1 and Table 2 may suggest increased sensitivity to climate variability at higher stocking rates.

Spring temperature influenced beef production (as shown by large effect estimates that were robust to standard errors) at both heavy and moderate stocking rates, but not at light stocking rates (Table 2). Spring precipitation also influenced beef production at heavy and moderate (but not light) stocking rates, with estimates being less robust (Table 2). Spring temperature and precipitation were correlated in this system, because warmer springs were drier, and cooler springs were wetter (linear regression: [Apr–Jun precip.] $= 454.81 - 26.27^{*}$ [Apr–Jun mean temp.]; $R^2 = 0.29$; $P < 0.0001$; $F = 32.04$; data not shown). Summer temperature and precipitation were not correlated in this system, but both positively influenced beef production differentially by stocking rate. Summer temperature had a robustly positive influence on beef production at heavy, but not moderate or light, stocking rates. Although summer precipitation had positive influences at the heavy and moderate stocking rates, the estimates were not robust. Interaction terms between temperature and precipitation for both spring and summer were small and generally not robust at any stocking rate. Prior-year fall/winter (March–October) and growing season (April–September) precipitation had a negative (but largely nonrobust) influence on beef production across stocking rates. The largest and most robust prior-year effect was prior–growing season precipitation at the light stocking rate (Table 2).

DISCUSSION

Our hypothesis of greater sensitivity to weather variables at higher stocking rates was supported, in that the proportion of variation explained (R^2 values) and effect size estimates decreased with decreasing stocking rate. Similarly, our hypothesis that increased spring (April–June) and summer (July–September) precipitation would benefit beef production was supported at moderate and heavy stocking rates, which concurs with Derner et al. (2008), at least for spring precipitation. In contrast, our hypothesis that temperature would be relatively unimportant was not supported. Cooler spring temperatures were highly beneficial to beef production at both moderate and heavy stocking rates. These cooler temperatures are optimal for

Table 3. Summary temperature and precipitation data across study years.

	Precipitation (mm)				Average temperature (°C)	
	Prior Apr–Sep	Prior Oct–Mar	Apr–Jun	Jul–Sep	Apr–Jun	Jul–Sep
Range	120.0–506.8	28.19–190.8	71.4–342.0	53.6–263.7	7.2–13.1	12.6–19.8
Mean (± SD)	312.0 (± 97.7)	108.4 (± 43.1)	192.7 (± 68.7)	136.9 (± 57.9)	10.0 (± 1.4)	17.1 (± 1.5)
Median	324.6	105.0	196.1	135.4	10.2	17.1

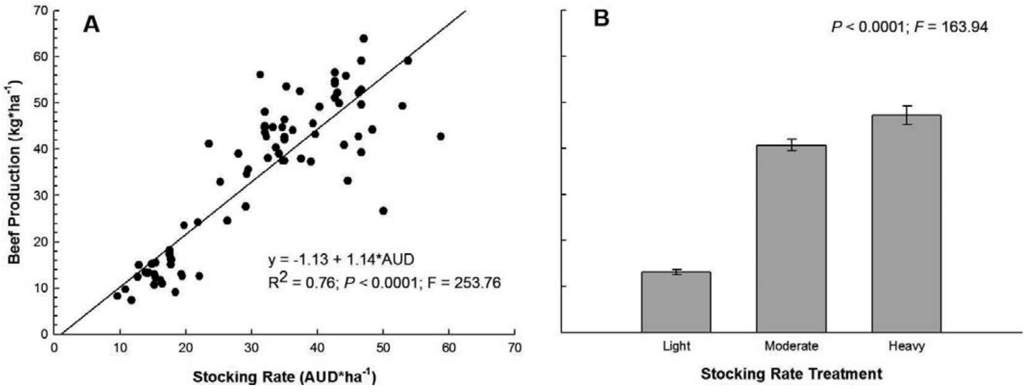

Figure 1. Continuous and categorical effects of stocking rate on beef production in northern mixed-grass prairie. A, Linear regression results of beef production using AUD · ha^{-1} as a continuous variable. B, *P*- and *F*-values resulting from analysis of variance (ANOVA). Error bars represent mean ± 1 SE. Tukey's honestly significant difference test showed significant differences ($P < 0.05$) between all treatments.

cool-season (C_3) grass growth (Williams 1974) and can increase intake by steers (Fox 1987) of these nutritious grasses (Barbehenn et al. 2004). Summer temperature also had a relatively and unexpectedly strong positive relationship with beef production at the heavy stocking rate, where the plant community is dominated by C_4 grasses (Manley et al. 1997) that can be more productive at warmer temperatures (Williams 1974). In contrast, a negative relationship between summer temperature and beef production was shown in a C_3-dominated northern mixed-grass prairie in eastern Montana (MacNeil and Vermeire 2012). These contrasting results demonstrate the importance of vegetation composition as a determinant in influencing the magnitude and directionality of temperature effects on beef production.

Temperature effects on beef production may have been inadvertently and perhaps detrimentally overlooked previously. Because precipitation has been shown to be important for forage production in this (and other) systems (Derner and Hart 2007), the resulting agronomic perspective of rangeland productivity may have led to less ecological focus on temperature. Though temperature variables had the largest effect sizes compared to the precipitation and interaction variables, the effect size between these variables are not directly comparable. Temperature coefficient estimates represent beef production responses based on 1°C intervals, whereas precipitation was based on 1-mm intervals. Given that temperature and precipitation are on two substantially different scales, the reader is cautioned against an interpretation that temperature is a much stronger predictor than precipitation. Temperature effect sizes were the most robust when compared to their respective standard errors, however (Table 2).

Warm, dry springs are detrimental to beef production, especially at moderate and heavy stocking rates, where composition of C_3 grasses is reduced in this northern mixed-grass prairie (Manley et al. 1997). One strategy to combat these negative effects would be to reduce stocking rates prior to the grazing season in years with expected warm, dry spring conditions. Though this strategy may be logistically difficult for many producers and relies on the accuracy of spring forecasts, yearling steers can be the most flexible and profitable type of cattle for adaptive management in this manner (Ritten et al. 2010; Torell et al. 2010). Because beef production with light stocking rates is relatively unaffected by climatic variability, utilizing lighter stocking rates increases predictability of gains and reduces enterprise risk when climatic conditions are unfavorable. A light stocking rate provides increased forage production and capacity to produce sustained beef production across variable climate conditions (Derner and Hart 2007), due to a more mixed C_3–C_4 grass community (Manley et al. 1997).

In contrast to warm, dry springs reducing beef production at heavy and moderate stocking rates, a combination of cool, wet springs and warm, wet summers are ideal for beef production in this mixed C_3–C_4 prairie. This can likely be attributed to growing conditions conducive to increased forage production occurring both early (C_3 grasses) and late (C_4 grasses) in the grazing season (Williams 1974; Smoliak 1986). Forage quality, as determined by both N content (Biondini et al. 1998) and leaf:stem ratio (Sims and Singh 1978), can also be positively influenced by increased precipitation in mixed-grass prairie. Thus, cool, wet springs and warm, wet summers provide environmental conditions for forage at both a quality and quantity sufficient for increased beef production at moderate and heavy stocking rates.

Prior growing season (April–September) precipitation negatively impacted current-year beef production under light stocking. Greater precipitation in the prior growing season would have increased plant production, which subsequently increases the amount of standing dead forage with light stocking in the current year (Derner and Hart 2007). Increased standing dead forage, especially reproductive stems of bunchgrasses such as needle-and-thread (which contain high lignin content [Milchunas et al. 2005]) in this system, may reduce forage quality on offer to grazing animals. Low forage quality can in turn alter grazing behavior (Ganskopp et al. 1992), which may contribute to lowered beef production.

We acknowledge that cattle genetics varied over these three decades, although British breeds (Hereford, Black Angus) were used consistently; as such, we cannot separate the effects of climatic factors and livestock genetics. In addition, consistent application of stocking rate treatments to the same pastures each year resulted in cumulative changes to vegetation composition (Manley et al. 1997) and forage productivity (Derner and Hart 2007) across years. At least a portion of the resultant influence of temperature and precipitation effects on beef production is therefore a product of long-term, grazing-induced modifications to plant communities in this northern mixed-grass prairie. Similarly, stocking rate variability across years within a treatment, due to differing grazing season lengths and minor fluctuations in numbers of grazing animals, likely contributed to the unexplained variation in our livestock-weather models. Even still, clear trends (which should be the focus here as much as the exact variable coefficients) could be seen for the effects of seasonal temperature and precipitation on beef production in northern mixed-grass prairie. These results highlight the utility and importance of long-term datasets such as the one presented here.

IMPLICATIONS

Under the parsimonious model structure presented here, ranchers would only be required to provide six easily accessible weather variables/forecasts for a decision support tool. Given that NOAA provides seasonal, three-month forecasts for any three-month period up to a year in advance, ranchers would have the ability to make at least some stocking rate decisions well in advance of the upcoming grazing season. This would potentially reduce degradation of the rangeland, allow for sustainable beef production, and increase economic returns through use of flexible stocking rates across years (Ritten et al. 2010; Torell et al. 2010). Enhancing decision-making related to stocking rate well before the grazing season would provide ranchers with the capacity to incorporate adaptive management for climate variability and increase their ability to optimize marketing strategies.

Inclusion of relationships between temperature and precipitation and beef production in relevant decision support tools such as the Great Plains Framework for Agricultural Resource Management (GPFARM; Shaffer et al. 2000; Andales et al. 2005, 2006), would enable ranchers to compare expected beef production at various stocking rates based on predicted weather and enable them to make strategic management decisions. Because many ranchers decide to maximize stocking rate in an effort to maximize profits (Dunn et al. 2010), ranchers using this strategy can be cautioned, based on our results that heavy stocking rates are most sensitive to climatic variability, to incorporate seasonal weather variables in their stocking rate decisions. Beyond annual expectations of beef production based on weather forecasts, long-term projections of beef production based on relevant climate change scenarios can also be produced by including our model averaged relationships in decision support tools such as GPFARM. Such long-term projections will be valuable in efforts to increase food production to accommodate a growing human population, especially in the face of climate change and variability (Food and Agriculture Organization of the United Nations 2011).

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