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Seasonal weather influences on yearling beef steer production in C$_3$-dominated Northern Great Plains rangeland☆

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ABSTRACT

In the face of an increasingly variable climate, long-term cattle weight gain datasets are rare, yet invaluable, for determining site-specific influences of seasonal weather patterns on cattle production. Here, we present a long-term (1936–2005) yearling Hereford steer dataset collected at the Northern Great Plains Research Laboratory (NPGRL) near Mandan, ND, USA. Data were analyzed using weighted AICc model averaging 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 prior fall/winter (prior October–March) precipitation on cattle production (kg/ha) under light (37.4 ± 5.3 SD Animal Unit Days [AUD]/ha across all study years) and heavy (91.6 ± 22.2 SD AUD/ha) stocking rates. Because Kentucky bluegrass (*Poa pratensis* L.) invaded the grassland at NPGRL in the early 1980s, we modeled cattle production separately for pre- (1936–1983) and post-invasion (1986–2005) years to determine if the plant community shift influenced sensitivity to seasonal weather patterns. Cattle production under heavy stocking was more sensitive to seasonal weather variability than under light stocking during both pre- and post-invasion years. Interestingly, the magnitude and robustness of coefficients changed between the pre- and post-invasion years, with seasonal weather patterns explaining more cattle production variation during the post-invasion years. Though cattle sensitivity to seasonal weather patterns differed between light and heavy stocking for both pre- and post-invasion years, invasion status did change cattle response to weather. For example, cattle production in *P. pratensis* invaded pastures was more heavily influenced by cool, wet springs and wet prior grazing seasons than was production in un-invaded pastures. For cattle stocked heavily in native pastures, wet winters more strongly increased cattle production than in invaded pastures.

1. Introduction

Currently, a lack of long-term cattle weight gain datasets (Briske et al., 2011) makes it difficult to identify the impacts of seasonal weather patterns on rangeland cattle weight gains, largely because the efforts needed to detect long-term, large-scale changes in rangeland (and cattle) productivity are often prohibitive (Bestelmeyer et al., 2011). In the face of an increasingly variable climate, more work is needed to better understand site-specific influences of seasonal weather conditions on cattle production. A fuller understanding of seasonal weather impacts on rangeland cattle weight gains will not only help ranchers maximize marketing strategies and minimize enterprise risk, but it will also allow for sustained cattle production as the climate changes and becomes more variable. This will become increasingly important to meet the

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demand for an estimated increase of 200 million tonnes of animal protein per year by 2050 (FAO, 2011).

Several ecological and economic models have been developed to determine the potential impacts of climate change and variability on cattle production (e.g., Hanson et al., 1993; Andales et al., 2005; Mader et al., 2009; Ritten et al., 2010; Torell et al., 2010). However, these models have been limited by an inability to incorporate direct effects of seasonal weather patterns on cattle production. Incorporating direct weather effects into predictive decision support tools would greatly aid ranchers in optimizing stocking rate decisions (Derner et al., 2012). Fortunately, recent studies have begun to determine impacts of seasonal weather conditions on cattle production in the Northern Great Plains (e.g., Biondini et al., 1998; Derner et al., 2008; MacNeil and Vermeire, 2012; Reeves et al., 2013a,b). Spring (April–June) precipitation has been shown increase cattle production across multiple studies (Derner et al., 2008; Reeves et al., 2013a,b). However, multiple factors such as animal type (i.e., steers vs. cows-calf pairs; Reeves et al., 2013a,b), breed (Reeves et al., 2013b), and plant community composition (Reeves et al., 2013a; MacNeil and Vermeire, 2012) can influence how cattle respond to other seasonal weather conditions.

Beyond seasonal weather patterns, invasive plants can also influence cattle production. During the past century, many non-native plant species have invaded rangelands in the USA (Sheley et al., 2011), and many negative impacts of invasive plants on rangelands are known (Masters and Sheley, 2001). Specific impacts of invasive plants such as leafy spurge (*Euphorbia esula* L.; e.g., Lym and Kirby, 1987; Kronberg et al., 1993) and smooth brome (*Bromus inermis* Leyss; e.g., Vinton and Goergen, 2006) on rangelands and cattle have been studied. However, the influence of invasive perennial C_3 grasses such as Kentucky bluegrass (*Poa pratensis* L.) on cattle production on rangelands remains unclear. *P. pratensis* is a non-native grazing tolerant C_3 perennial that has been increasing in abundance on Northern Great Plains rangelands (Murphy and Grant, 2005; Travnicek et al., 2005). *P. pratensis* reduces plant diversity and alters seasonal forage distribution on rangeland, which has led to research on plant control (Hendrickson and Lund, 2010). Following *P. pratensis* invasion in the 1980s at the study site reported here (see below), one goal of this study was to determine if and how *P. pratensis* invasion impacted cattle production response to seasonal weather patterns.

The USDA-Agricultural Research Service (ARS) Northern Great Plains Research Laboratory (NGPRL) near Mandan, ND, USA has collected data on yearling Hereford beef steer production on native rangeland at different stocking rates from 1936 to 2005. This long-term dataset was analyzed to examine effects of seasonal temperature and precipitation on cattle production. The grassland at NGPRL has predominantly C_3 grasses (see Section 2.1), so cool, wet springs and summers should increase forage (C_3 grass) production (Williams, 1974; Sage and Kubien, 2007). Thus, we hypothesized that cattle production would be greater during years with cool, wet springs and summers (Hypothesis 1; Reeves et al., 2013a; MacNeil and Vermeire, 2012). We also hypothesized that cattle production under heavy stocking would be more sensitive to seasonal weather variability than under low stocking (Hypothesis 2) because the reduction in forage available per animal under heavy stocking would be exacerbated when weather conditions were detrimental for forage production (Reeves et al., 2013a; MacNeil and Vermeire, 2012). Finally, because the plant community at NPGRL began changing in the early 1980s following invasion by *P. pratensis*, we modeled pre-invasion years (1936–1983) and post-invasion years (1986–2005) separately to compare possible changes in seasonal weather effects following the plant community shift.

2. Materials and methods

2.1. Site description

The following descriptions of the design and conduct of the long-term grazing experiment at NGPRL near Mandan, ND (46°46′12″N; 100°54′57″W) were taken from Sarvis (1920, 1923), Rogler and Haas (1947), and Rogler (1944, 1951). Mean annual (88 yr) precipitation is 414 mm with about 75% occurring between April and September. Mean annual temperature is 4°C, with daily averages ranging from 21 °C in summer to −11 °C in winter. This upland site is uniform in slope (0–3%) and the soils are Temvik–Wilton silt loams (fine-silty, mixed, superactive, frigid Typic and Pachic Haplustolls). The primary ecological site is loamy (site ID R054X031ND). The site has been managed without the use of fertilizer, herbicides, or fire.

The perennial C_4 grass blue grama (*Bouteloua gracilis* [H.B.K.] Lag. ex Griffiths) and perennial C_3 graminoids including needle-and-thread (*Hesperostipa comata* [Trin. & Rupr.] Barkworth), western wheatgrass (*Pascopyrum smithii* [Rydb.] Löve), prairie junegrass (*Koeleria macrantha* [Ledeb.] Schultes), and sedges (*Carex* sp.) dominated the vegetation in 1916 (Sarvis, 1920). During the severe drought of the 1930s, *P. smithii* became the dominant grass. In the early 1980s, *P. pratensis* (C_3) was observed in the pastures and by 1994 was rapidly increasing in abundance (Frank et al., 1995). Subsequent botanical estimates in 2004 and 2011 indicated that *P. pratensis* had nearly completely displaced *B. gracilis* (NGPRL, unpublished data). Data from a site approximately 73 km northwest of the study site showed similar increases in *P. pratensis* and decreases in native grasses during the same time period (DeKeyser et al., 2009).

2.2. Grazing experiment

The original study objective was to determine the effect of different stocking rates on vegetation and liveweight gains of cattle (Sarvis, 1923). Data have been collected each year since 1916. Of the original experimental pastures, grazing and record keeping of two pastures has continued to present: the heavy stocking rate pasture (12.1 ha; one steer per 1.2 ha), and the light stocking rate pasture (40.5 ha; one steer per 4.0 ha). For these experimental pastures, sites were originally chosen that were similar in slope, soils, and vegetation. Cattle used in experiments were all owned by private ranchers in the local area. The stocking rates chosen in 1916 were considered “heavy” and “light” stocking rates at that time. The current stocking rate recommendation for this loamy ecological site in central North Dakota is about 0.8 ha per yearling steer per month (based on animal unit-month stocking rate tables in Sedivec and Printz (2012). For consistency with previous reports and clarity we retained the “heavy” and “light” descriptors in this paper.

Pastures were stocked continuously each year from mid-May until early/mid-October, and cattle were weighed throughout each grazing season (beginning and end weights were used for calculations below). Frequently, however, to ensure animal welfare, cattle had to be removed early from the heavy stocking rate pasture because forage had been depleted ($n = 37$ yr where season length was shorter for heavy stocking than light stocking; Table 1). Across study years, the size of the 12.1 (heavy stocking) and 40.5 ha (light stocking) pastures was reduced to accommodate other research; however, the stocking rates remained similar.

Over the course of the entire study (1916–present), steer breeds and ages (i.e., yearlings vs. two-year-olds) varied. However, yearling Hereford steers were used consistently from 1936–2005. To remove likely confounds associated with different animal breeds and ages across years, only these years when yearling Hereford steers were grazed were used in the analyses. Similarly, only years with data for both the light and heavy stocking rate pastures were

Table 1
Pasture size, number of steers, yearly on-off dates (in month/day format), and stocking rates for yearling Hereford steers during pre- (1936–1983) and post-*P. pratensis* invasion (1986–2005) years. Pasture entry dates were the same for each treatment except in 1967 when cattle in the heavy stocking rate treatment entered pasture on 31 May. *L* = light stocking rate treatment; *H* = heavy stocking rate treatment. Missing years (1937, 1952–1955, 1977, 1984–1985, 1988, 1990) exist when cattle were either not grazed or historical data were missing. An animal unit equivalent of 0.75 was used in calculating stocking rates (AUD/ha; Holechek et al., 1998).

Year	Pasture Sz (HA)		No. steers		Date on	Date off		Days		AUD/HA	
	L	*H*	*L*	*H*	●	*L*	*H*	*L*	*H*	*L*	*H*
1936	40.5	12.1	10	10	5/26	8/29	8/29	95	95	17.6	58.7
1938	40.5	12.1	10	10	5/21	10/13	10/13	145	145	26.9	89.6
1939	40.5	12.1	10	10	5/11	10/13	10/13	155	155	28.7	95.8
1940	40.5	12.1	10	10	5/16	10/13	10/13	150	150	27.8	92.7
1941	40.5	9.3	13	10	5/26	10/3	10/3	130	130	31.3	104.3
1942	40.5	9.3	13	10	5/16	10/13	10/13	150	150	36.1	120.3
1943	40.5	9.3	13	10	5/11	10/13	10/13	155	155	37.3	124.4
1944	40.5	9.3	13	10	5/16	10/13	10/13	150	150	36.1	120.3
1945	40.5	9.3	13	10	5/16	10/13	10/13	150	150	36.1	120.3
1946	40.5	9.3	13	10	5/6	10/13	9/13	160	130	38.5	104.3
1947	40.5	9.3	13	10	5/21	10/13	10/13	145	145	34.9	116.3
1948	40.5	9.3	13	10	5/16	10/13	9/28	150	135	36.1	108.3
1949	40.5	9.3	13	10	5/11	10/3	8/29	145	110	34.9	88.3
1950	40.5	9.3	13	10	5/30	10/3	8/29	125	90	30.1	72.2
1951	28.3	9.3	13	10	5/16	10/3	8/29	140	105	48.2	84.2
1956	28.3	9.3	11	10	5/16	10/3	9/12	140	120	40.8	96.3
1957	28.3	9.3	11	10	5/16	10/3	9/13	140	120	40.8	96.3
1958	28.3	9.3	11	10	5/16	10/3	8/29	140	105	40.8	84.2
1959	28.3	9.3	11	10	5/16	10/3	7/30	140	75	40.8	60.2
1960	28.3	9.3	11	10	5/16	10/3	9/12	140	120	40.8	96.3
1961	28.3	9.3	11	10	5/16	10/3	7/10	140	65	40.8	68.2
1962	28.3	9.3	11	10	5/16	10/3	10/3	140	140	40.8	112.3
1963	28.3	9.3	11	10	5/16	10/3	9/8	140	115	40.8	92.3
1964	28.3	9.3	11	10	5/16	10/3	8/29	140	105	40.8	84.2
1965	28.3	9.3	11	10	5/16	10/3	9/23	140	130	40.8	104.3
1966	12.9	2.8	5	3	5/16	10/3	8/24	140	100	40.8	80.2
1967	12.9	2.8	5	3	5/16	10/3	8/24	140	85	40.8	68.2
1968	12.9	2.8	5	3	5/16	10/3	8/29	140	105	40.8	84.2
1969	12.9	2.8	5	3	5/16	10/3	9/13	140	120	40.8	96.3
1970	12.9	2.8	5	3	5/21	10/3	8/29	135	100	39.3	80.2
1971	12.9	2.8	5	3	5/11	10/3	8/29	145	110	42.3	88.3
1972	12.9	2.8	5	3	5/16	10/3	9/13	140	120	40.8	96.3
1973	12.9	2.8	5	3	5/16	10/3	7/20	140	65	40.8	52.1
1974	12.9	2.8	5	3	5/14	10/8	8/30	145	105	42.3	84.2
1975	12.9	2.8	5	3	5/22	10/6	8/28	137	98	39.9	78.6
1976	12.9	2.8	5	3	5/20	9/9	7/7	102	48	29.7	38.5
1978	12.9	2.8	5	3	5/17	10/4	9/12	140	118	40.8	94.7
1979	12.9	2.8	5	3	5/23	9/28	8/16	128	85	37.3	68.2
1980	12.9	2.8	5	2	5/21	9/10	6/4	112	14	32.6	7.5
1981	12.9	2.8	4	2	5/26	10/7	8/26	134	92	31.2	49.2
1982	24.6	2.8	6	3	5/21	10/7	9/9	139	111	25.4	89.1
1983	12.9	2.8	4	3	5/18	10/5	9/7	140	112	32.6	89.9
Pre-invasion											
Mean	●	●	●	●	●	●	●	139	111	36.8	86.7
SD	●	●	●	●	●	●	●	12.3	30.1	5.89	23.4
1986	15.4	2.8	5	3	5/28	10/15	10/15	140	140	34.0	112.3
1987	15.4	2.8	5	3	5/27	10/6	9/23	132	119	32.1	95.5
1989	15.4	2.8	6	3	5/19	9/29	8/10	133	83	38.8	66.6
1991	15.4	2.8	6	3	5/17	9/27	9/6	133	112	38.8	89.9
1992	15.4	2.8	6	3	5/14	10/1	10/1	140	140	40.9	112.3
1993	15.4	2.8	6	3	5/20	10/7	10/7	140	140	40.9	112.3
1994	15.4	2.8	6	3	5/19	10/6	10/6	140	140	40.9	112.3
1995	15.4	2.8	6	3	5/19	10/6	10/6	140	140	40.9	112.3
1996	15.4	2.8	6	3	5/17	10/4	10/4	140	140	40.9	112.3
1997	15.4	2.8	6	3	5/22	10/9	10/9	140	140	40.9	112.3
1998	15.4	2.8	6	3	5/21	10/8	9/30	140	132	40.9	105.9
1999	15.4	2.8	6	3	5/25	10/12	10/12	140	140	40.9	112.3
2000	15.4	2.8	6	3	5/25	10/11	10/11	140	140	40.9	112.3
2001	15.4	2.8	6	3	5/24	10/10	10/10	140	140	40.9	112.3
2002	15.4	2.8	6	3	5/31	10/17	10/10	140	132	40.9	105.9
2003	15.4	2.8	6	3	6/12	10/9	9/22	119	102	34.7	81.8
2004	15.4	2.8	6	3	5/25	9/10	9/10	109	109	31.8	87.4
2005	15.4	2.8	6	3	6/1	10/4	10/4	126	126	36.8	101.1
Post-invasion											
Mean	●	●	●	●	●	●	●	135	129	38.7	103
SD	●	●	●	●	●	●	●	8.84	16.9	3.28	13.6

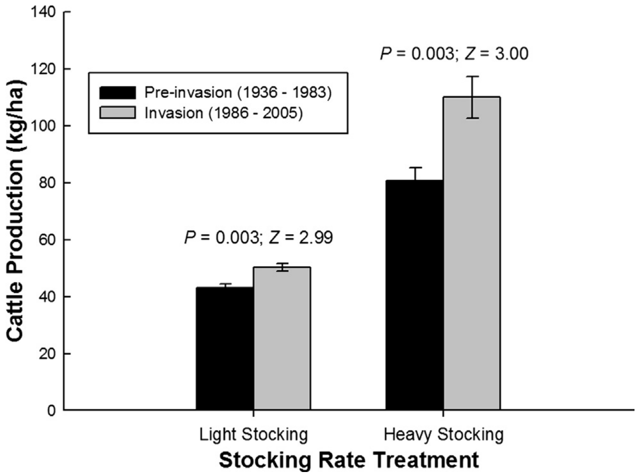

Fig. 1. Comparison of mean cattle production (kg/ha) between stocking rate treatments during pre- (1936–1983) and post- (1986–2005) *P. pratensis* invasion years. Bars represent mean±1 SE. *P*-values and *Z*-values are results from Wilcoxon tests. Significant differences in cattle production between pre- and post-invasion years may have been driven by a higher stocking rate in the post-invasion years (Table 1). Precipitation was generally higher during the post-invasion years as well (Table 2).

included in the analyses. Some years (data) were missing either because cattle were not grazed or because historical data could not be found. See Table 1 for a summary of yearly dates and stocking rates for each pasture (treatment) used in this study. For the analyses below, total cattle production (kg/ha) was calculated for each treatment by dividing the sum of steer seasonal weight gains by the number of total hectares in the respective pastures (Reeves et al., 2013a,b).

2.3. Statistical analyses and model fitting

Because plant community composition can strongly influence forage (Smart et al., 2007) and therefore cattle (MacNeil and Vermeire, 2012; Reeves et al., 2013a,b) response to weather, and since the plant community shifted at NGPRL, we divided the data set into pre- (1936 to 1983) and post-*P. pratensis* invasion years (1986 to 2005). These sets of years were modeled separately to examine likely differences in cattle production response to seasonal weather patterns based on the different plant communities (i.e., more C_4 vs. almost totally C_3-dominated in pre- vs. post-*P. pratensis* invasion, respectively). Though analyses across all years combined were also performed, confounds associated with differing cattle responses to weather by plant community were clearly evidenced by much lower R^2 values and smaller coefficients in the overall model (data not shown here) than for the separated results presented below. Because important weather variables from each plant community competed with each other in the overall model, results from combining data become difficult to clearly interpret and thus are perhaps not as meaningful. Further, Wilcoxon tests were used to test for differences in cattle production between the pre- and post-invasion years. Production differences between these years (Fig. 1) also justified that we modeled the pre- and post-invasion years separately. As in Reeves et al. (2013a), we modeled the light and heavy stocking rate pastures separately to examine our hypothesis that cattle production in the heavy stocking rate pasture would be more sensitive to seasonal weather variability than cattle production at light stocking.

To examine the influences of seasonal weather patterns on cattle production under pre- vs. post-invasion status at each stocking rate, model averaging methodology in JMP 10.0.0 (SAS Institute Inc., 2012; as in Reeves et al., 2013a,b) was used. This method calculates averaged model coefficients using corrected Akaike Information Criterion (AICc) weights (SAS Institute Inc., 2012; http://www.jmp.com/support/help/The_Model_Averaging_Option.shtml). The fitting and averaging of multiple competing models accounts for model uncertainty and selection procedure bias, thereby preventing selection of a poor model (Wang et al., 2009). Model averaging tends to produce accurately predictive models (SAS Institute Inc., 2012), which can often be more accurate than many “best-model” methods (Burnham and Anderson, 2004). Burnham and Anderson (2004) and Wang et al. (2009) provide model averaging reviews.

Because our models had nine total variables (see below), we used a maximum of nine variables for individual models. For selection of models to be averaged, an AICc cutoff weight of 0.95 was used (SAS Institute Inc., 2012), meaning that out of all possible models, those models that make up 95% of the total AICc weight (sum of all individual AICc weights) were used to calculate weighted coefficient averages. Since model averaging is an information-theoretic approach, results must be interpreted and inferred from outputs without corresponding *P*-values. Information-theoretic approaches can provide many benefits over traditional null hypothesis testing and interpretation of *P*-values, as they do not rely on arbitrary declarations of “significance” (Anderson et al., 2000).

To minimize both spurious effects and over-fitting of the data, our selected model structure was based on parsimony and a priori hypotheses (rather than “data dredging”; Anderson et al., 2001). The selected model structure was also chosen to maximize utility for decision support tools (Derner et al., 2012), as it aggregated climatic data into three-month periods to parallel the three-month weather forecasts available from the National Atmospheric and Oceanic Administration (NOAA) (http://www.nws.noaa.gov/predictions.php). Further, current-season weather data were aggregated into three-month periods because three-month periods of precipitation were shown by Derner et al. (2008) to be better predictors of cattle production than individual months in northern mixed-grass prairie.

To account for potential genetic differences across years, average steer weights at the start of the grazing season were used in the models (initial weights increased with time over study period; Avg. Start weight = −3981.8 + 2.2 × Year; $R^2 = 0.80$; $P < 0.0001$ [data not shown]; as in Reeves et al., 2013b). In addition to initial weights, we included the same eight weather variables as Reeves et al. (2013a,b). Included were total precipitation (mm) and average (of average) temperature values (°C; mid-point between maximum and minimum temperatures) for both spring (April–June) and summer (July–September) of the current grazing season. An interaction term of precipitation × temperature was also included for the spring and summer variables in the event that effects of temperature and precipitation were not simply additive. Since previous year precipitation and forage production can affect forage production in the current year (Oesterheld et al., 2001), prior growing season (April–September) and prior fall/winter (October–March) precipitation, but not temperature, were also included in the model. All weather data used here were acquired from the High Plains Regional Climate Center (Mandan Experiment Station; station no. 325479).

The chosen model structure was created under a hypothesis exploration framework (Anderson et al., 2001), while also maximizing both biological meaning and management tool utility (Derner et al., 2012). The model structure was selected to best match study goals rather than to provide the best fit, but most complicated and intricate possible model. It should be noted that model coefficients were not standardized since the aims of this study were use these models for predictive purposes, as well as to compare results to similar studies. As a result, because precipitation (mm) and temperature (°C) values were on different scales, resulting coefficients for these two types of variables are not directly comparable. Because the standard errors for each coefficient indicate coefficient bias towards zero (SAS Institute Inc., 2012), coefficient estimates that were larger than their respective standard errors were considered to be particularly robust (important) predictors of cattle production (Reeves et al., 2013a,b). The term "robust" will hereafter be used to describe variables that were considered to be more accurately predictive and thus important components of the presented models.

3. Results

As expected, cattle production was higher under heavy stocking than light stocking (Fig. 1), and weather was highly variable during the study period (Table 2), both for the pre- (1936–1983) and post-*P. pratensis* invasion (1986–2005) years. During the pre-invasion years, the precipitation values showed anywhere from a three-fold (prior April–September) to a 14-fold (April–June) difference between low and high yearly values. For the temperature variables, a 5.4 °C range existed between low and high years for April–June average temperature, whereas a 6.4 °C range existed between low and high July–September yearly values. Correspondingly, for the post-invasion precipitation values, a range of three-fold (prior April–September) to eight-fold (prior October–March) existed across years. Post-invasion temperatures had a range of 4.3 °C for April–June, and a range of 4.6 °C for July–September. Note that mean precipitation values were higher during post-invasion years, particularly for summer (July–September) and prior growing season (prior April–September).

3.1. Model results for pre-invasion years (1936–1983)

During the pre-invasion years, robust coefficients differed for the heavy and light stocking rate treatments. For the heavy stocking rate treatment, animal entry weight had a robust negative effect on cattle production, while spring (April–June) precipitation, spring precipitation × temperature interaction, and winter (prior October–March) precipitation all had robust positive effects on cattle production (Table 3). The robust spring precipitation × temperature interaction term under heavy stocking may indicate that the importance of spring precipitation increases as spring temperatures increase, though interaction terms in the context of model averaging can be difficult to interpret and need more research (Dochtermann and Jenkins, 2011). For the light stocking rate treatment, spring and summer (July–September) temperature showed robust negative effects on cattle production, with robust positive effects of spring precipitation and spring precipitation × temperature interaction (Table 3). Fig. 2 shows relative robustness for each variable under each stocking rate as calculated from Table 3. With the exception of spring and summer temperatures, model-averaged coefficients were higher for the heavy stocking rate, as was the R^2 value, indicating that cattle production under heavy stocking was more sensitive to seasonal weather variability.

3.2. Model results for post-invasion years (1986–2005)

As with pre-invasion years, during post-invasion years, robust coefficients differed between the heavy and light stocking rate treatments. Under heavy stocking, spring precipitation, winter precipitation, and prior growing season (prior April–September) precipitation all had robust positive effects on cattle production. Spring temperature had a large, robust negative effect on cattle production as well (Table 3). Under light stocking, spring temperature had a smaller but still robust negative effect on cattle production, along with a negative effect of spring precipitation × temperature interaction, and a positive effect of prior winter precipitation (Table 3). Fig. 3 shows relative robustness for each variable under each stocking rate as calculated from Table 3. In many instances, coefficient estimates were larger under heavy stocking than light stocking, as was the R^2 value, again indicating that cattle production under heavy stocking was more sensitive to seasonal weather variability.

4. Discussion

We accepted our first hypothesis that cool, wet springs and summers would increase cattle production in this C_3-dominated northern mixed-grass prairie. Higher cattle production was associated with greater spring precipitation for heavy stocking during both pre- and post-*P. pratensis* invasion years. Cool spring temperatures were also shown to increase cattle production for light stocking during pre-invasion years, and for both light and heavy stocking during post-invasion years. Similarly, cool summers were shown to increase cattle production under light stocking during pre-invasion years. These seasonal weather variables likely increased cattle production through favorable growing conditions for C_3 grasses (Williams, 1974; Sage and Kubien, 2007; Derner and Hart, 2007).

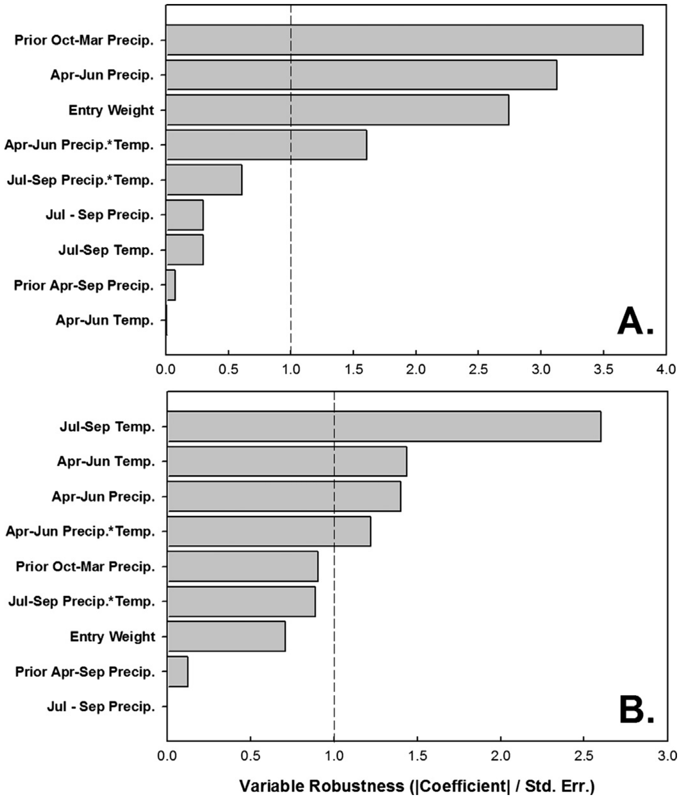

Fig. 2. Relative variable robustness for pre-*P. pratensis* invasion years (1936–1983). Panel A represents heavy stocking rate treatment; panel B represents light stocking rate treatment. Values were calculated by dividing coefficient estimates from Table 3 by their corresponding standard errors. Bars extending beyond the dashed line indicate that the coefficient was larger than its standard error and thus considered robust (as described above). Absolute values of coefficients were used in figure calculations. Refer to Table 3 for coefficient signs. Note that variable robustness as shown here does not necessarily indicate variable effect size.

Our second hypothesis that cattle production under heavy stocking would be more sensitive to weather variability than under light stocking was also supported. More of the variation in cattle production for heavy stocking was explained by seasonal weather variables than for light stocking, both for pre- and post-invasion years. Many of the coefficient estimates were also larger for heavy compared to light stocking for both pre- and post-invasion years, indicating that seasonal weather variables had a larger impact on cattle production under heaving stocking (though the unstandardized coefficients make it somewhat difficult to directly compare coefficients). Because forage availability per animal was already experimentally reduced for heavy stocking, further reductions in forage availability through poor weather conditions should decrease cattle production more under heavy than light stocking. This finding is consistent with prior observed results from other northern mixed-grass prairie studies (e.g., Derner et al., 2008; Reeves et al., 2013a).

Prior growing season (prior April–September) and prior fall/winter (October–March) precipitation were shown to increase cattle production differentially by stocking rate and invasion status. For instance, prior growing season precipitation increased cattle production at only the heavy stocking rate during post-invasion years, though prior fall/winter precipitation increased cattle production in all instances except light stocking during pre-invasion years. Prior precipitation increased cattle production likely because both prior growing season (Oesterheld et al., 2001) and prior winter (Chimner and Welker, 2005) precipitation can increase forage

Table 2
Summary seasonal weather data during study period with year of extreme values in parentheses. Data are shown separately for pre- vs. post-*P. pratensis* invasion periods. Summary data include only years during which cattle were grazed (as shown in Table 1).

		Precipitation (mm)				Avg. temperature (°C)	
		Prior Apr–Sep	Prior Oct–Mar	Apr–Jun	Jul–Sep	Apr–Jun	Jul–Sep
Pre-invasion (1936–1983)	Mean	329.3	84.5	180.1	139.3	11.8	18.8
	SD	66.6	37.2	66.5	58.2	1.2	1.2
	Low	183.6 (1974)	21.8 (1961)	24.1 (1936)	44.7 (1976)	9.0 (1950)	15.9 (1965)
	High	555.5 (1966)	200.9 (1983)	352.6 (1975)	283.0 (1951)	14.4 (1980)	22.3 (1936)
Post-invasion (1986–2005)	Mean	374.5	94.1	185.5	196.9	12.4	18.7
	SD	120.2	53.6	66.4	81.3	1.1	1.3
	Low	195.8 (1989)	28.7 (1991)	90.4 (2002)	84.8 (2003)	10.9 (1996)	16.0 (1992)
	High	614.9 (1994)	230.9 (1995)	319.0 (1999)	395.0 (1993)	15.2 (1987)	20.6 (1998)

production in the current year. Similarly, early research at NGPRL showed forage and cattle production on native rangeland were positively correlated with soil moisture in the prior fall and with April to July precipitation in the current production year (Rogler and Haas, 1947). Further, grazing research on *P. pratensis*-dominated grassland near Streeter, ND, USA showed a positive relationship between grass production and the total amount of precipitation received since the end of the growing season in the previous year (Patton et al., 2007). For both native C_3-dominated rangeland and *P. pratensis*-dominated rangeland, prior growing season and winter precipitation is critical for land managers employing heavy stocking rates. In contrast to heavy stocking, light stocking leaves greater vegetative and litter cover (Manley et al., 1997; Derner and Hart, 2007), both of which contribute to greater retention of soil water. This buffers variation in response to precipitation (Patton et al., 2007) and thus perhaps reduces reliance on prior growing season and prior fall/winter precipitation for light stocking.

Model results largely conformed to site-specific vegetation composition, with model results differing for pre- and post-*P. pratensis* invasion years. Because the current (i.e., post-invasion) plant community at NGPRL is predominately C_3-grass dominated, forage production can be expected to increase with cool, wet springs (Williams, 1974; Derner and Hart, 2007). Cattle production was tightly coupled to these same environmental factors, which may be ideal for cattle (not just forage) as well (Ames, 1980). Coefficients increased for spring temperature and precipitation (especially at the heavy stocking rate) during the post-invasion compared to the pre-invasion years, as did overall model R^2 values. Thus, model results indicated that cool, wet springs became especially important for forage production in the post-*P. pratensis* invasion years. This can perhaps be attributed to *P. pratensis* being most productive in early spring when temperatures are cool and soil moisture levels relatively high (Wedin and Huff, 1996). During the pre-invasion years, composition of blue grama in the plant community was higher with heavy than light stocking (NGPRL, unpublished data). As such, the robust negative effect of summer temperatures with light, but not heavy, stocking can be explained by the increased proportion of C_3 grasses being negatively impacted by warmer temperatures (Williams, 1974). When C_4 grasses are a greater component of the plant community in northern mixed-grass prairie, the corresponding weather variables that influence cattle production change to be coupled with C_4 grass production (i.e., warm, wet summers; Reeves et al., 2013a). The importance of considering plant community composition when using seasonal weather conditions to predict forage and cattle production is highlighted here (Smart et al., 2007), as is the corresponding importance of site-specificity for decision support tools.

Models presented here explained up to 74% of the variation in yearling Hereford steer cattle production (Table 3). However, multiple factors may contribute to the remaining ≥26% of variation. For instance, stocking rates varied in some years (Table 1), and since stocking rate can influence yearling steer production (e.g., Derner et al., 2008; Reeves et al., 2013a), this stocking rate variation may account for some of the unexplained variance. All years (regardless of stocking rate) were left in the models, however (Reeves et al., 2013a,b), as stocking rate variation was due to grazing seasons being shortened because of poor weather and forage depletion, and because stocking rate is such a strong determinant of cattle production that it can override weather effects in these models if included as a covariate. In addition to stocking rate variation, changes in animals across years may have also influenced cattle production. Steer entry weights were the best available method to account for animal changes across years given the data (Reeves et al., 2013b), and entry weight did show a robust negative effect on beef production

Table 3
Model averaged coefficients for entry weight and seasonal weather effects on yearling Hereford steer cattle production (kg/ha) during both pre-(1936–1983) and post-(1986–2005) *P. pratensis* invasion years. Sample sizes (*n*) in column headers represent the number of models that were used in calculating weighted coefficient averages. Bolded values indicate coefficients where means were greater than standard error, indicating robustness of that variable. Note that the coefficients are unstandardized.

Variable	Pre-invasion (1936–1983)				Post-invasion (1986–2005)			
	Stocking rate				Stocking rate			
	Heavy (*n* = 76)		Light (*n* = 261)		Heavy (*n* = 76)		Light (*n* = 120)	
	Estimate	Std. error	Estimate	Std. error	Estimate	Std. error	Estimate	Std. error
Intercept	88.255	●	103.803	●	114.005	●	65.450	●
Animal Entry Weight	−**0.324**	**0.118**	0.017	0.024	0.005	0.043	−0.012	0.019
Apr–Jun precipitation	**0.172**	**0.055**	**0.021**	**0.015**	**0.343**	**0.087**	0.001	0.007
Apr–Jun avg. temperature	0.009	1.344	−**1.188**	**0.826**	−**8.798**	**3.810**	−**0.909**	**0.682**
(Apr–Jun precipitation)*(Apr–Jun avg. temperature)	**0.045**	**0.028**	**0.011**	**0.009**	0.003	0.032	−**0.041**	**0.018**
Jul–Sep precipitation	0.009	0.030	0.000	0.011	0.003	0.018	0.001	0.005
Jul–Sep avg. temperature	0.445	1.494	−**2.784**	**1.070**	0.051	0.996	−0.128	0.338
(Jul–Sep precipitation)*(Jul–Sep avg. temp)	0.014	0.023	0.008	0.009	0.009	0.016	0.000	0.003
Prior Apr–Sep. precipitation	0.002	0.027	−0.001	0.008	**0.084**	**0.035**	0.000	0.003
Prior Oct–Mar precipitation	**0.374**	**0.098**	−0.019	0.021	**0.094**	**0.069**	**0.023**	**0.016**
Coefficient of determination (R^2)	0.56		0.44		0.74		0.55	

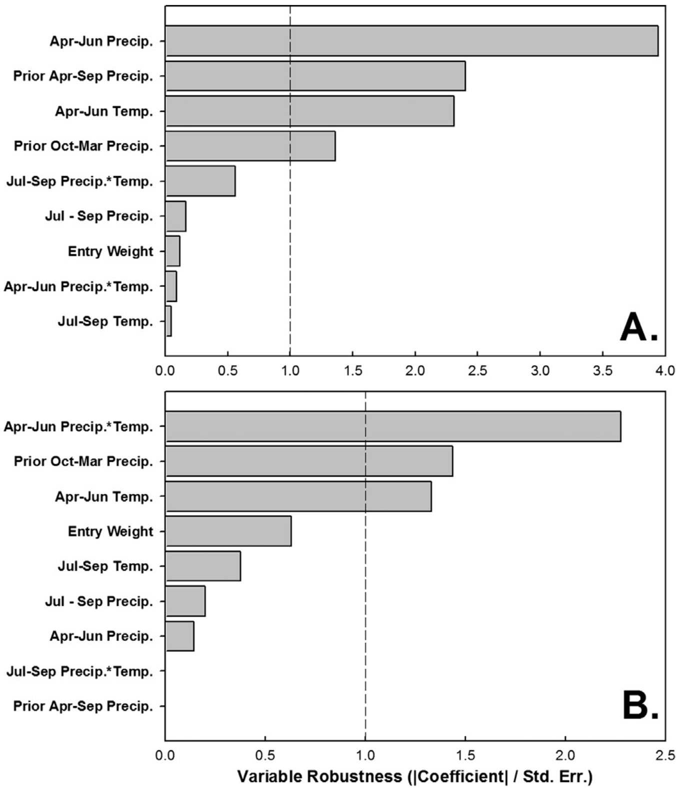

Fig. 3. Variable robustness for post-*P. pratensis* invasion years (1986–2005). Panel represents heavy stocking rate treatment; panel B represents light stocking rate treatment. Values were calculated by dividing coefficient estimates from Table 3 by their corresponding standard errors. Bars extending beyond the dashed line indicate that the coefficient was larger than its standard error and thus considered robust (as described above). Absolute values of coefficients were used in figure calculations. Refer to Table 3 for coefficient signs. Note that variable robustness as shown here does not necessarily indicate variable effect size.

under the heavy stocking rate during pre-invasion years. Animal genetic changes (other than those associated with the increasing entry weights across study years), along with potential variations in source or handing of animals (i.e., supplements) prior to grazing season across years, also could have influenced cattle production. We had no data or information to be able to account for these other potential influences, however.

Because stocking rates are often maximized in an effort to maximize profits (Dunn et al., 2010), ranchers can be cautioned based on our model results that heavy stocking will make them more sensitive to seasonal weather effects. To reduce enterprise risk associated with inherently variable seasonal weather conditions, improved decision support tools could assist ranchers making stocking rate decisions based on seasonal weather forecasts. Decision support tools such as the Great Plains Framework for Agricultural Resource Management (GPFARM; Shaffer et al., 2000; Andales et al., 2005, 2006) can be improved by incorporating information about direct seasonal weather impacts on cattle production. Furthering the utility of decision support tools such as GPFARM by including weather variables that are forecasted up to a year in advance (such as the three-month seasonal forecasts from NOAA as noted above) would allow stocking rate alternatives/options to be presented to ranchers well in advance of the grazing season. For example, ranchers who normally use heavy stocking rates and graze both cow-calf pairs and yearlings could sell (or relocate) some of their animals in early spring if precipitation during the previous year was lower than normal and current winter/early spring precipitation was also poor. Ranchers who implement lighter stocking rates may have forage from the previous growing season to graze and may not need to destock under such conditions. Matching stocking rates to expected seasonal weather conditions can be problematic for cow-calf only producers, but producers with a yearling steer component in their enterprise can have higher flexibility for this sort of adaptive management (Ritten et al., 2010; Torell et al., 2010).

5. Conclusion

We analyzed a long-term (1936–2005) yearling Hereford steer weight gain dataset to determine the effects of seasonal weather patterns and *P. pratensis* invasion on cattle production in a C_3-dominated northern mixed-grass prairie. Heavy stocking rates were more sensitive to seasonal weather variability than light stocking rates. Prior growing season precipitation, fall/winter precipitation, cool and wet springs, and cool summers, increased cattle production differentially by stocking rate and *P. pratensis* invasion status. Producing user-friendly decision support tools (Derner et al., 2012) that incorporate free, web-based seasonal weather forecasts will ultimately reduce rancher enterprise risk. As more long-term cattle weight gain datasets are analyzed, decision support tools will become increasingly useful and site-specific. This will not only assist rancher decision-making, but will also increase food security to provide animal protein to accommodate the growing world population (FAO, 2011).

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J.T. Sarvis established the experiment in 1915 and managed it until 1940. The experiment was continued by George Rogler (1940 to 1952), Russell Lorenz and G. Rogler (1953 to 1973.), R. Lorenz (1974 to1979), Lenat Hofmann (1980 to 1992), and Jim Karn (1993 to 2002). Numerous technicians and part-time students were also involved in the day-to-day management and conduct of the experiment. We would like to recognize these scientists and support staff for their extraordinary foresight and determination in adaptively managing and continuing this experiment for more than 90 years. Finally, the producers who provided study cattle over the course of the study are thanked for their invaluable contributions.

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