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Beef production and net revenue variability from grazing systems on semiarid grasslands of North America

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ABSTRACT

Sustainability of ranches and rural economies in the Great Plains of western North America is contingent on the economic vitality of beef production in a changing climate. Our objective was to measure and compare the interannual variability of beef production (kg/ha) and net returns ($/ha) over the past 15 years (2003–2017) from grazing yearlings at three different grazing intensities (light, moderate and heavy) on semiarid shortgrass steppe from mid-May to October. Four useful insights emerged: 1) A ranking of interannual variability, from lowest to highest, reveals that beef production had the lowest coefficient of variation (CV = 17–29%), followed by aboveground net primary production (ANPP, 26–32%), spring/early summer precipitation (36%) and net revenue (107–139%). 2) Beef production increased with grazing intensity during average and wet years, but not during dry years. Beef production increased from early August to early September but became negligible from early September to the end of the grazing season. Overall, beef production and net revenue were 41% and 38% greater for the heavy grazing intensity compared to the recommended moderate grazing intensity, respectively. 3) Removing yearlings from pastures in early September rather than the traditional October timing would provide opportunities for ranchers to increase net returns. 4) Forage production, estimated through remote sensing information, was positively associated with beef production, but with a steeper slope for the heavy grazing intensity, indicating greater sensitivity at this grazing intensity level. Economic sustainability of beef production in this rangeland ecosystem is challenged by high interannual variability in net revenues. This variability suggests that ranchers should focus on understanding agricultural economic principles, livestock marketing, and available options for reducing price risk. These efforts would enhance both the economic sustainability of individual ranching operations and rural economies.

1. Introduction

The vitality of rural communities in the western North American Great Plains is contingent on the economic sustainability of beef cattle ranching in a changing climate (Derner et al., 2018). Interannual variability in precipitation, aboveground net primary production (ANPP), beef production, and net returns make decision-making in this region especially challenging. By understanding the relative ranking of interannual variability among these biophysical, ecological, and economic factors, ranchers can better prioritize their management efforts within these complex social-ecological systems (Wilmer et al., 2017).

Complicating the comparison of interannual variability, however, is the range of possible grazing intensities, from heavy to moderate to light. Heavy grazing intensities generally provide greater net returns, on average, to ranchers in the western Great Plains (e.g., Hart and Ashby 1998; Dunn et al., 2010). Plant communities in this region have a long evolutionary history with grazing ungulates, resulting in inherent resistance (Milchunas et al., 1988). Less well understood, however, is the implication of grazing intensity for variability in net returns for ranching enterprises.

As precipitation variability increases in the western Great Plains under a changing climate (Easterling et al., 2017), variation in economic returns is also projected to increase (Hamilton et al., 2016). To make matters worse, positive economic returns in wet years are not expected to overcome negative economic returns in dry years (Hamilton et al., 2016). One adaptation strategy ranchers have

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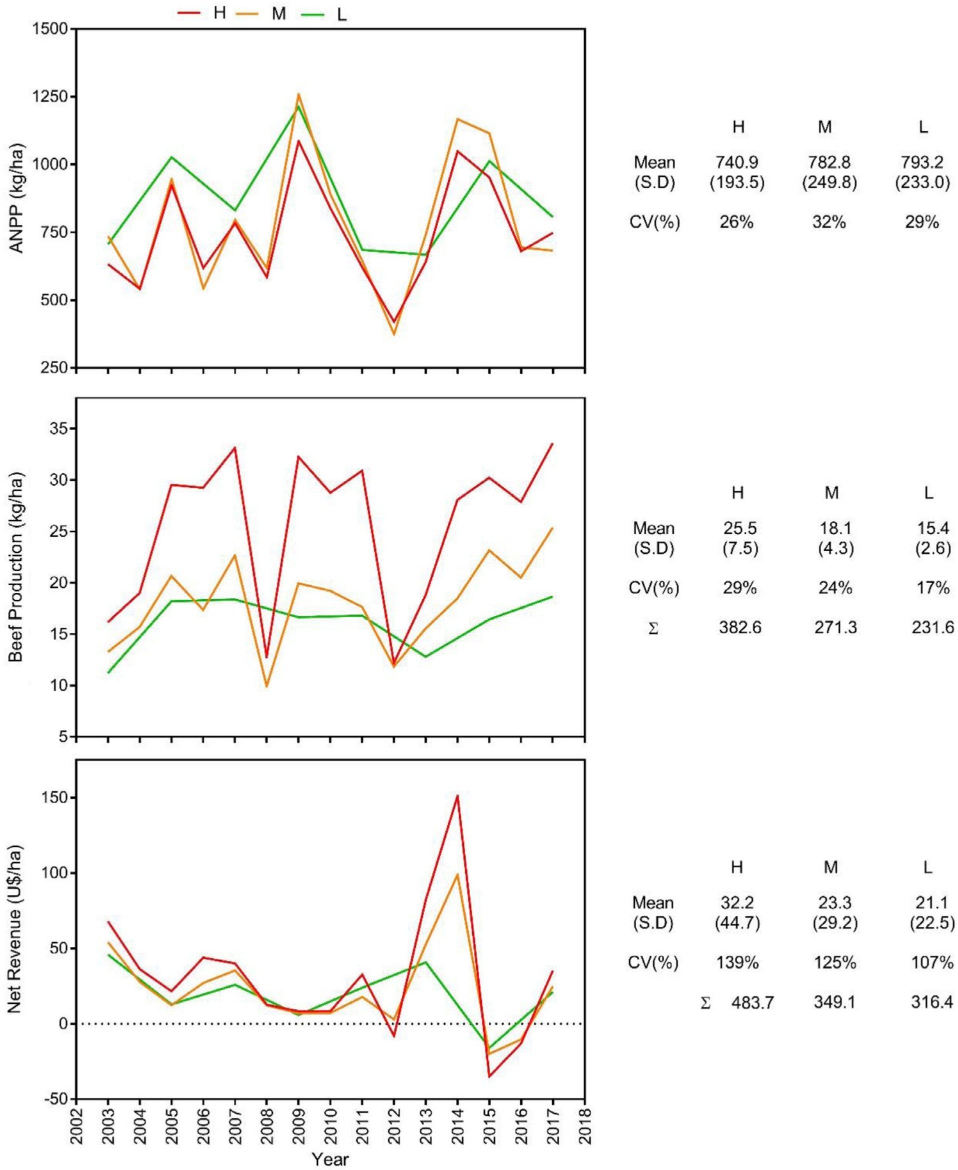

Fig. 1. Temporal dynamics of Aboveground Net Primary Production (ANPP), Beef Production, and Net Revenue for three long-term grazing intensity treatments—H: Heavy (18.5 AUD/ha), M: Moderate (12.5 AUD/ha) and L: Light (9.3 AUD/ha). Beef production and net revenue represent the accumulated values from mid-May to October. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

employed to increase operational flexibility in environments with highly variable precipitation and forage production (Hart and Ashby 1998; Derner and Hart 2007) is the use of yearling cattle (stockers) for grazing rather than traditional cow-calf grazing. Incorporating yearlings into a ranching operation can increase economic returns through increased flexibility in matching forage availability with animal demand (Ritten et al., 2010; Torell et al., 2010). For those who distrust the completely transition to stockers, ranch profitability can still be increased by replacing a portion of the cow herd with yearlings, again for increased flexibility in matching forage availability to animal demand (Hamilton et al., 2016).

Our objective was to measure and rank the interannual variation in beef production (kg/ha) and net returns ($/ha) from grazing yearlings in the semiarid, shortgrass steppe from mid-May to October over the past 15 years (2003–2017) at three different grazing intensities (light, moderate and heavy). With this in mind, we established two specific objectives: (1) to evaluate how weather conditions and management strategies (grazing intensity, removal date for grazing) influence the interannual variability of aboveground net primary production (ANPP, kg/ha), individual animal weight gains (kg/yearling/day), total beef production (kg/ha), and net revenue ($/ha), and (2) establish the type of relationships (linear or nonlinear) between ANPP and beef production during the latter part of the grazing season (August, September and October).

2. Materials and methods

2.1. Site characteristics

Research was conducted on the USDA-Agricultural Research Service Central Plains Experimental Range in north-central Colorado, USA (40°49′ N, 107°46′ W), a Long-Term Agroecosystem Research (LTAR) Network site. The primary ecological site is Loamy Plains (Site ID: R067BY002CO). Mean annual precipitation during the study period (2002–2017) was 334 ± 61 mm (mean ± standard deviation [SD]) and April–July precipitation was 191 ± 68 mm.

Precipitation in spring and early summer (April–July) strongly influences ANPP in the region (Lauenroth and Sala 1992; Derner et al.,

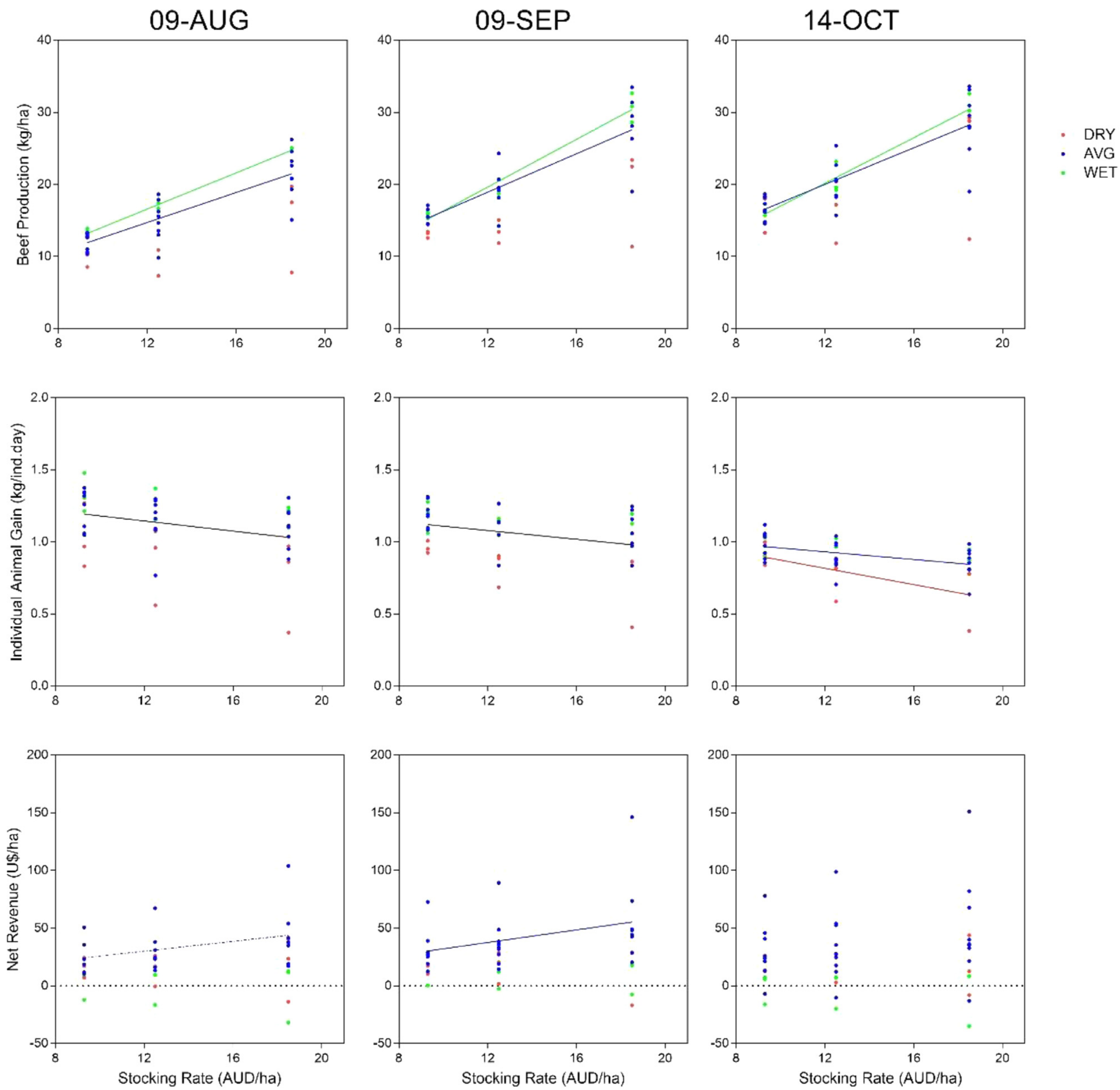

Fig. 2. Relationships between beef production (upper panel), Individual Animal Gain (middle panel) and Net Revenue (lower panel) relative to stocking rate (AUD/ha). Points represent the mean value and lines represent the fitted linear regressions (solid lines were statistically significant at $p < 0.05$, the dotted line was statistically significant at $p < 0.08$). Lines in colors indicates the fitted model by type of year. The black line indicates a common model across type of years. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
ANOVA test results. Fixed factors included: grazing intensity, type of year (Dry, Average, Wet), and grazing period. Statistically significant factors ($p < 0.05$) are bolded.

Factors	Beef production *F*	*p*	Individual gain *F*	*p*	Net revenue *F*	*p*
Grazing intensity (GI)	**105.01**	**<0.0001**	**12.67**	**<0.0001**	0.64	0.52
Type of Year (TY)	**46.58**	**<0.0001**	**67.19**	**<0.0001**	**21.21**	**<0.0001**
Period (P)	**145.12**	**<0.0001**	**12.24**	**<0.0001**	0.68	0.5000
GI × TY	**5.33**	**0.0005**	0.95	0.4346	1.09	0.3600
GI × P	**4.25**	**0.0001**	0.17	0.9950	0.03	0.9999
TY × P	1.24	0.2814	**4.61**	**<0.0001**	0.16	0.9999
GI × TY × P	0.16	0.9999	0.18	0.9999	0.01	0.9999

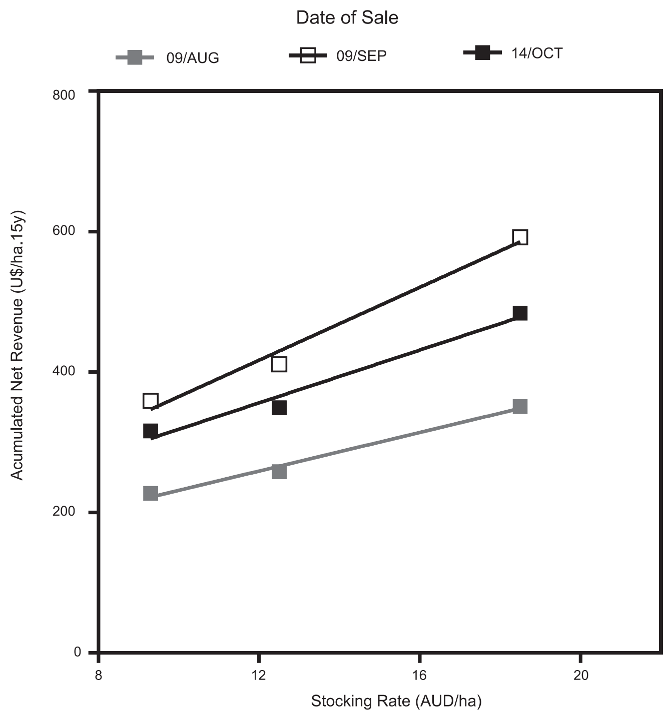

Fig. 3. Relationships between Accumulated Net Revenue over the 15-year analyzed period (2003–2017) relative to stocking rate (AUD/ha). Points represent the accumulated value at each stocking rate treatment. Lines represent the fitted linear regressions ($p < 0.08$) for each possible date of sale (day/month).

2008a) and thus beef production (Derner et al., 2008b). Plant composition at the study site is predominately perennial shortgrass species. The dominant warm-season (C4) species is *Bouteloua gracilis* (Willd. ex Knuth) Lag. ex Griffiths (blue grama), which increases with increasing grazing intensity (Porensky et al., 2017). Important cool-season (C3) mid-height grasses include *Pascopyrum smithii* (Rydb.) A. Löve (western wheatgrass) and *Hesperostipa comata* (Trin. & Rupr.) Barkworth (needle-and-thread). The primary cool-season graminoid is *Carex duriuscula* C.A. Mey (needle leaf sedge). The primary forb is *Sphaeralcea coccinea* (Nutt.) Rydb. (scarlet globemallow), and the main sub-shrubs are *Artemisia frigida* Willd. (fringed sagewort) and *Eriogonum effusum* Nutt. (buckwheat). Annual grasses, when present, consist almost entirely of *Vulpia octoflora* (Walter) Rydb. (six weeks fescue).

2.2. Grazing treatments

A grazing experiment was initiated at the study site in 1939, comprising four levels of grazing intensity: (1) none; (2) light (targeted for 20% utilization of peak growing-season biomass); (3) moderate (40% utilization); and (4) heavy (60% utilization) (Hart and Ashby 1998). British-breed yearlings were typically grazed from mid-May to October. Pasture sizes were approximately 129 ha. Stocking rates used to achieve the desired grazing intensities were 9.3 animal unit days (AUD) per ha (light), 12.5 AUD/ha (moderate), and 18.5 AUD/ha (heavy) within the study period (from 2000 to 2015). With increasing grazing intensity, grazing and harvest efficiency increase (Smart et al., 2010), and C4 grass biomass (Irisarri et al., 2016) increases, but C3 graminoid biomass decreases (Irisarri et al., 2016) and individual animal weight gains also decrease (Bement 1969; Hart and Ashby 1998). Plant community composition is similar between the heavy and moderate grazing intensity treatments, but differs under the light grazing intensity treatment (Porensky et al., 2017). Bare soil is greater with heavy grazing intensity compared to moderate intensity (Augustine et al., 2012).

2.3. Livestock and vegetation data

Individual animal weights were obtained at the beginning of each grazing season, approximately every 28 days during the grazing season, and at the end of each grazing season. Yearlings were either held overnight without feed and water prior to weighing (2003–2012), or gathered and weighed with a shrink adjustment (2013–2017) (Derner et al., 2016). Individual animal gain (kg/yearling/day), also known as average daily gain, was estimated using cumulative grazing season gain divided by the number of grazing days. Beef production (kg/ha) was calculated by summing the cumulative gains of all yearlings over the grazing season divided by the pasture area. Within-season beef production was also estimated for early-August and early-September weigh dates, to inform an economic evaluation of alternative marketing dates (see below).

ANPP was estimated monthly in each pasture, from 2003 to 2017, following the radiative model of Monteith (1977). This model estimates ANPP as the triple product of photosynthetic incoming radiation (PAR), its proportion absorbed by active vegetation (fPAR), and the radiation use efficiency (RUE) or conversion of radiation absorbed to biomass. Daily PAR data were obtained from a meteorological station located at the study site. fPAR was obtained through a non-linear transformation of NDVI (Normalized Difference Vegetation Index) as proposed by Grigera et al. (2007) and calibrated against ANPP from natural pastures across wide regional gradients (Irisarri et al., 2012; Caride et al., 2012; Durante et al., 2017). Finally, RUE (0.24 g C/MJ) and a conversion ratio (0.48 g C/g dry matter: 0.5 g DM/MJ) were obtained from Paruelo et al. (1997) for the U.S. Great Plains, inclusive of our study site.

2.4. Economics

Purchase cost and sale revenue for each yearling in each year were calculated by multiplying its live weight by the livestock price reported for the week in which the yearling was turned out and removed from pasture, respectively. If a price was not reported for a specific weight class in a given week, an estimate was calculated as a linear combination of prices for adjacent weight classes during that same week. Livestock prices were obtained from the Livestock Marketing Information Center (LMIC), which relies on data compiled by the USDA-Agricultural Marketing Service. Forage leasing cost ($/animal unit month, AUM) was estimated for each year using the 11 U.S. western states lease rates (Wyoming Agricultural Statistics Service (WASS) Internet site: https://www.nass.usda.gov/Statistics_by_State/Wyoming/index.php). All monetary variables were normalized to 2017 (using the Producer Price Index, PPI). Net revenue for each yearling over the entire growing season was determined by subtracting the yearling purchase cost and forage leasing cost from the sale revenue. Net revenue was also calculated using the early-August and early-September within-grazing season weigh dates, rather than the end-of-season weigh date in October.

2.5. Data analysis

To address our first research question—the influence of weather conditions and management decisions on interannual variability of individual animal weight gain, beef production, and net revenue—we performed ANOVA tests using the independent factors of precipitation year-type (wet, average, dry), grazing intensity (light, moderate, heavy), and period within the grazing season (August, September, and October). We defined “wet” years (2009, 2010, and 2015) as those with spring/early-summer precipitation exceeding the mean (191.1 mm) + 1 SD (68.0 mm). We defined “dry” years (2006, 2008, and 2012) as those with spring/early-summer precipitation below the mean - 1 SD. We categorized all other years (2003, 2004, 2005, 2007, 2011, 2013, 2014, 2016, 2017) as “average.” We then used linear

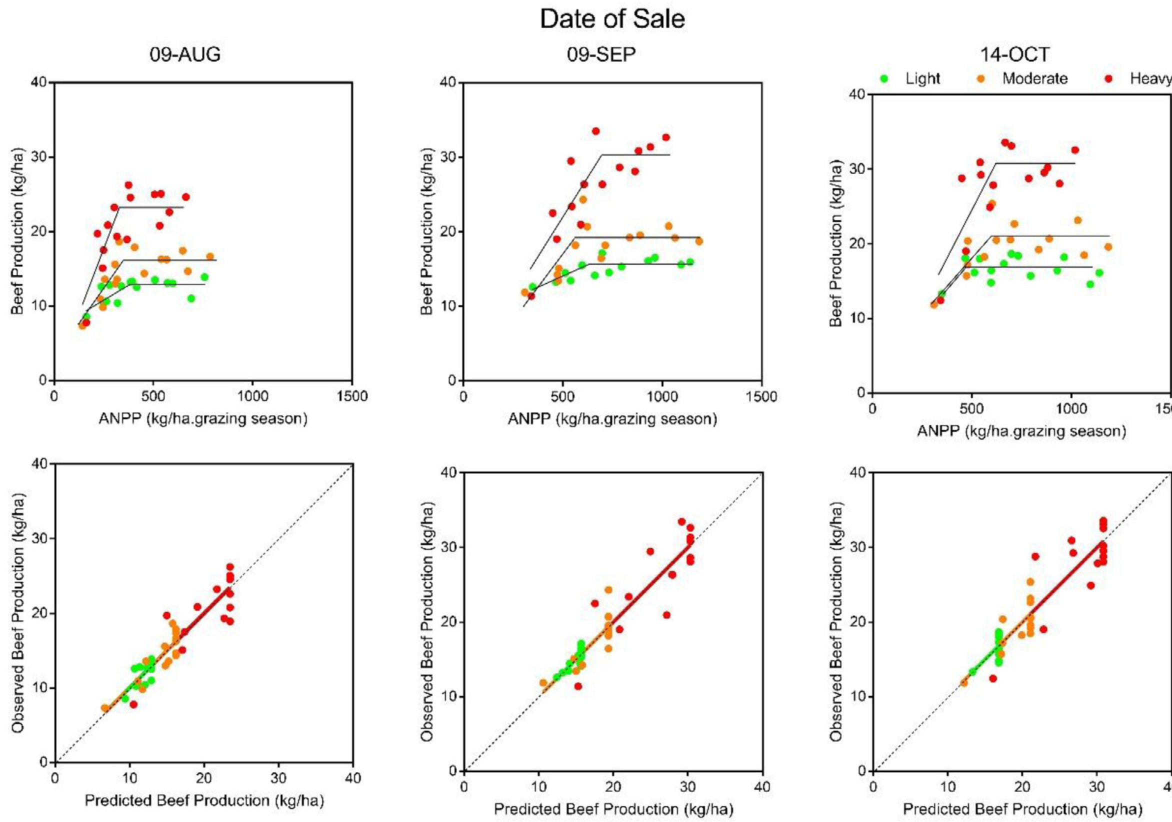

Fig. 4. Upper panels: relationships between beef production and accumulated ANPP 30 days before the specific date of sale. Lower panels: observed *vs.* predicted beef production. Points represent beef production and ANPP data observed in individual years of the study and for different grazing treatments. In the upper panels, black lines represent the fitted nonlinear regressions. In the lower panels, color lines represent the fitted model between observed and predicted beef production (using the nonlinear regressions described in the upper panels and Table 2); the dotted line represents a 1:1 relation. Each column of panels represents an alternative date of sale. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Results of two regression models between beef production and accumulated ANPP through date of sale. The linear model consisted of a second-degree polynomial association between beef production and accumulated ANPP. The nonlinear piecewise regression model consisted of a saturation type association up to a plateau.

Observed *vs* Predicted Treatment	Date of sale	AIC linear	AIC non linear	Adj. R^2	RMSE
Heavy	09-AUG	79.60	**78.06**	0.69	11.31
	09-SEP	80.76	**80.18**	0.68	17.96
	14-OCT	82.03	**81.42**	0.61	22.17
Moderate	09-AUG	68.08	**61.51**	0.76	3.09
	09-SEP	69.69	**64.6**	0.65	5.5
	14-OCT	68.81	**66.30**	0.60	5.53
Light	09-AUG	51.83	**50.72**	0.51	1.63
	09-SEP	38.97	**37.89**	0.66	0.72
	14-OCT	54.61	**54.34**	0.29	2.20

regression to evaluate the influence of precipitation year-type and stocking rate on three dependent variables of interest—individual animal weight gain, beef production, and net revenue.

To address our second research question—about the functional form of the relationship between ANPP and beef production during the last three months of the grazing season—we focused on the accumulated ANPP and beef production during August, September, and October. Accumulated ANPP was defined as the sum of ANPP from the start of the grazing season through the cattle weigh date within the grazing season. We used two regression techniques: 1) a linear regression model, and 2) a nonlinear, piecewise regression model, which finds a natural breakpoint and adjusts a linear regression to the segment before the break point and a plateau above it (Dorronsoro et al., 2002). We chose the most parsimonious model based on the lowest AIC value. Finally, we tested the accuracy of the fitted model by estimating a linear regression between the observed versus predicted beef production values (Piñeiro et al., 2008).

3. Results

3.1. Interannual variability

Interannual variability in vegetation production (ANPP) was similar among grazing intensities, with coefficients of variation (CV) ranging between 26–32% across the 15 study years. No statistically significant differences in mean ANPP were observed among grazing intensities. However, ANPP for the light grazing intensity treatment had higher ANPP in dry years (2006, 2008, 2012) when compared to the moderate and heavy treatments (Fig 1, upper panel).

Looking next at beef production, its interannual variability increased monotonically from 17% CV at light grazing to 29% CV with heavy grazing (Fig 1, middle panel). During the dry years of 2008 and 2012, beef production dropped precipitously in the heavy and moderate grazing treatments. Yet, across the entire study period, heavy grazing produced 65% more total beef than light grazing and 41% more than moderate grazing.

Interannual variability in net revenue ranged from 107% CV with light grazing to 139% CV with heavy grazing (Fig 1, lower panel). Such CVs are 3 to 5-fold greater than those for ANPP and beef production. Net revenue was largest in 2014, whereas they were negative in the very next year (2015). Mean net revenue (averaged across years) was 38% greater for heavy grazing ($32.20/ha) than for moderate grazing

($23.30/ha), and 53% greater than for light grazing ($21.10/ha). Cumulatively, over the 15 years, heavy grazing returned $134.60/ha more than moderate grazing and $167.30/ha more than light grazing.

3.2. Grazing intensity and precipitation effects

Beef production (kg/ha) increased with grazing intensity in average and wet years, but not in dry years (Fig 2, Table 1). Beef production increased from early August to early September for each level of grazing intensity, but negligible beef production was observed from early September to the end of the grazing season in mid-October (Fig 2).

Individual animal weight gains (average daily gain, kg/yearling/day) differed with grazing intensity, type of year, and grazing period (Table 1). During the final grazing period (early September to mid-October), individual animal gain decreased substantially with increasing grazing intensity when the year was dry (2006, 2008, 2012).

Net revenue ($/ha) was unaffected by grazing intensity (Table 1); however, it was influenced by type of year (Table 1), driven largely by record market sale prices in 2013 and 2014 (Fig 2). These two years were the only ones in the analyzed period in which the sale price was above the purchase price (data not shown), 6% and 11% respectively. On the contrary, in 2015 and 2016, and like the rest of the years, purchase price was above sale price. However, in these two years, the anomaly ((purchase-sale)/sale x 100) reached its maximum, 53% and 41% respectively, while the other years, without 2013 and 2014, this anomaly was in average 19% (this indicates that in average purchase value is 19% higher than sale value).

Cumulative net returns over the 15 years were consistently lowest if yearlings were removed from grazing and sold in early August, irrespective of grazing intensity (Fig 3). The greatest cumulative net returns were observed from removing the yearlings in early September, for all grazing treatments, with intermediate net returns occurring from the "business as usual" removal in October.

3.3. Vegetation and livestock production

Beef production was positively associated with accumulated ANPP to date through grazing periods 4, 5 and 6, under all grazing intensities (Fig 4, upper panels). We found that piecewise regression—a nonlinear method which finds a natural breakpoint, and adjusts a linear regression to the segment before the break point and the plateau above it—was a better fit to the data than simple linear regression. Focusing on the linear regression segment prior to the break point, we find a steeper slope for the heavy grazing intensity. This demonstrates greater sensitivity in beef production to accumulated ANPP to date under this treatment.

Using the piecewise regression models, accumulated ANPP explained 60–76% of variation in beef production across all grazing intensity levels and grazing periods, with the exception of period 4 (August, 51% of variation) and period 6 (October, 29% of variation) under the light grazing treatment (Table 2). For both the heavy and moderate grazing intensities, previously accumulated ANPP explained a higher proportion of the variation for beef production in August compared to October, with September falling between them.

4. Discussion

Our long-term study allowed us to point out four key findings in one of the largest remaining grassland areas of North America: (1) Profit variability is up to 5-folds higher than the most variable biophysical component, spring precipitation, the main control of ANPP (Derner and Hart 2007; Irisarri et al., 2016). (2) Management decisions, as setting stocking rate, only expresses its positive impact on beef production in wet and average years, but not in dry ones. Besides, removing grazing animals in early September, would have the same output, in terms of beef production, when compared to "business as usual" mid-October. (3) Moreover, removing the grazing animals beforehand (early September) would also have a positive impact on the long-term economic benefit. (4) The positive association between beef production and the accumulated ANPP of up to 30 days prior provides managers with a novel tool to improve their economic performance.

In the highly grazing-resistant, semiarid shortgrass steppe (Milchunas et al., 1988), economic sustainability of ranching enterprises is more closely tied to livestock market dynamics than to grazing management (Bement 1969; Hart and Ashby 1998). This is exemplified by our finding that net revenue had the highest interannual variability (107–139% CV) and beef production the lowest (17–29% CV). Beef production, in turn, was less variable than spring/early summer precipitation (36% CV), which is critical to ANPP in the study region (Derner and Hart 2007). This highlights the stability of beef production in this region despite its intrinsically high inter and intra-annual precipitation environment (Knapp and Smith 2001). Net revenue´s high volatility relative to beef production stability is a common feature to other beef grazing systems of the world (Pacín and Oesterheld 2014). Moreover, Beef production's relative stability compared to the primary abiotic resource, precipitation, is also a common feature among other grazing systems of the world (Irisarri et al., 2014).

Beef production in the semiarid shortgrass steppe is responsive to grazing intensity, with production increasing with grazing intensity in average and wet years, but not in dry years (2006, 2008 and 2012 for this study). In dry years, lower forage availability per grazing animal—i.e., a higher grazing pressure index (AUD/megagram of forage; Smart et al., 2010)—especially under the moderate and heavy grazing intensity, can limit intake and thus reduce individual animal weight gains (Bement 1969; Allison 1985; Derner et al., 2008b; Smart et al., 2010). Lower average daily gain by yearlings in these dry years (about 20% of the study years) negated the usual benefit of having more head under moderate grazing intensity (23 head) and heavy intensity (30 head), as compared to light intensity (15 head). This suggests that adaptive management strategies, in the form of herd-size flexibility, could better match forage availability with forage demand and provide a buffer against the negative impacts of dry years (Derner and Augustine 2016).

Cattle in the western Great Plains are generally stocked at heavier grazing intensities than the moderate intensity typically recommended (Dunn et al., 2010). Our results suggest an explanation for this behavior; specifically, that an increase in grazing intensity, from moderate to heavy, is associated with increases in beef production (41%) and net revenue (38%), with no notable shifts in the vegetation plant communities (Porensky et al., 2017). Cumulatively, over a 15 year study period, the heavy grazing treatment returned heavy grazing returned $134.60/ha more than moderate grazing treatment. This finding contrasts with that of O' Reagain et al. (2011) for dry tropical savannas in Australia, where heavy stocking resulted in the lowest net present value over a 12-year study and highest variability in profit. Beef production was also greater under a heavy stocking rate in O' Reagain et al. (2009), but only because the animals were fed during drought years, which comprised 40% of the study period.

One strategy for cattle ranchers to further increase net revenue from grazing yearlings on the semiarid shortgrass steppe is to remove them from pastures in early September, rather than mid-October (Fig 3). Although yearling steers gained weight from August to September, they gained negligible weight from early September to the end of the grazing season in mid-October. Ranchers may be tempted to capture any additional weight gain, even if negligible, because it seems nearly free at that point. It might also help them meet their buyer's desired time of delivery. However, our analysis shows that net revenue can be increased by removing them from pasture for an earlier sale date. Additionally, pulling yearlings off the range a month early could generate ecological advantages for the ecosystem, such as greater plant residue for soil cover, and a longer resting period.

Underscoring the potential benefits of a shortened grazing season in this system is the heightened sensitivity of beef production to accumulated ANPP in September and October, as compared to August (Fig 4, upper panel), particularly under heavy grazing. The steeper slopes in the far-right versus far-left graphs of Fig 4 (upper-panel) reflect the risk under heavy grazing of larger decreases in beef production during lower forage availability years. For cattle producers who actively monitor forage availability, this knowledge of accumulated ANPP to date can help them estimate the amount of additional beef production from grazing beyond August and into September or October.

5. Conclusion

Economically sustainable provision of beef production in the semi-arid shortgrass steppe is contingent on improving the resiliency of ranching operations in a changing climate. Here, findings from a 15-year study of yearlings grazing shortgrass steppe at light, moderate, and heavy intensities from mid-May to mid-October showcase that beef production under these grazing management strategies have low interannual variability (17–29% coefficient of variation). Concerns for the economic sustainability of beef production in this rangeland ecosystem emanate, however, from the high interannaul variability (107–139%) of net revenue for ranchers. This variability is mostly attributable to livestock price market dynamics, which are influenced by customer demand, cattle inventories and market cycles. Ranchers should therefore invest adequate time in understanding principles of agricultural economics, livestock marketing, and options for reducing market risk. These efforts would not only enhance the economic sustainability of individual ranching operations, but also the vitality of their rural economies.

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