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Rangeland Livestock Production in Relation to Climate and Vegetation Trends in New Mexico☆

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ABSTRACT

A large statewide historical database involving livestock numbers, vegetation cover, precipitation, air temperature, and drought frequency and severity allowed us to explore relationships between climate and rangeland livestock grazing levels and livestock productivity from 1920 to 2017. Trends in vegetation cover and livestock grazing levels from 1984 to 2017 were also explored. Our climate time series was divided into two periods, 1920 − 1975 and 1976 − 2017, based on an apparent accelerated increase in mean annual air temperatures that began in the mid-1970s. Both mean annual precipitation (MAP) and mean annual air temperature (MAT) differed ($P \leq 0.05$) between the two periods. MAP and MAT were 9.6% and 3.4% higher in period 2 compared with period 1, respectively. From the 1920s to 2010s the livestock grazing level and weaned calf numbers fell 30% and 40%, respectively, despite a significant increase in MAP. Long-term declines in livestock grazing levels and in weaned calf numbers were significantly ($P \leq 0.05$) correlated with increasing MAT ($r = -0.34$ and $r = -0.43$, respectively). No long-term trends (1984–2017) in woody or perennial herbaceous cover were detected at the level of the entire state of New Mexico. Woody plant cover dynamics for New Mexico were not related to livestock grazing levels. However, at the county level we detected a 2% increase in woody plant cover coupled with a 9% decrease in cattle animal units between 2000 and 2002 and 2015 and 2017 for 19 select counties well distributed across New Mexico. Increases in woody plant cover varied greatly among counties and were higher for eastern than western New Mexico. Both global and New Mexico data show the climate warming trend is accelerating. Our findings have relevance to several other parts of the world because New Mexico occurs at midlatitude, has varied topography and climatic conditions, and several different range vegetation types.

Introduction

In this research paper, we examine the long-term trend (1920 − 2017) in New Mexico rangeland livestock production in the context of important influencing factors focusing on climate change and woody plant cover. Studies of climate change impacts on rangeland livestock production are lacking for all parts of the world including the western United States. Recent reports project climate change will impact all rangeland ecosystems, but the greatest impacts will likely occur in semiarid and arid areas (Polley et al., 2013; IPCC, 2014; Havstad et al., 2016; USGCRP, 2017, 2018).

Rangelands account for roughly 70% of the world's land area and ~16% of global food production (Holechek, 2013). Rangeland livestock production is especially important in meeting food needs of pastoral societies across Africa, central Asia, and many parts of South America (Holechek, 2013; Holechek et al., 2017; WRI, 2018). In the United States, rangeland livestock production is important to local economies throughout the Great Plains, Intermountain West, and Southwest (Holechek et al., 2011; Field, 2018). It plays a key role in the nation's beef supply through production of calves that later go to feedlots (Field, 2018). Both world food and meat demand are rapidly increasing, which is elevating the importance of rangelands in terms of feeding the world's growing human population (Brown, 2012; Palmer, 2017; WRI 2018).

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Although there are many projected adverse impacts on humans from continued global warming, the biggest threat involves sharply depressed food production (Dyer, 2010; Randers, 2012; IPCC, 2014; Wallace-Wells, 2017). In order to prevent a future world food crisis, research on the impacts of global warming on the various aspects of world agriculture is of critical importance in formulating adaptation and mitigation measures. Understanding the timeline regarding how quickly the global warming process is occurring will be essential for rangeland livestock producers to develop sound proactive management strategies (Joyce et al., 2013). Within the United States, the southwest portion, which includes New Mexico (~92% rangeland), is projected to encounter the greatest warming and drying throughout this century (Polley et al., 2013; Havstad et al., 2016; USGCRP, 2017, 2018). Because of its geographic location (midlatitude), wide diversity of rangeland ecosystems, and the importance of rangeland livestock production to its economy, New Mexico is potentially a useful indicator of how climate change is impacting semiarid and arid rangelands in other parts of the world.

In New Mexico a large statewide historical database has been collected on rangeland livestock numbers, precipitation, air temperature, and drought frequency and severity. This database provides an opportunity to examine climatic trends over the period from 1920 to 2017 in relation to New Mexico's rangeland livestock production. The specific objectives of our study were first to determine if differences occurred in New Mexico's annual precipitation (cm) levels and annual average daily air temperatures (°C) among decades and between two periods (1920 to 1975 and 1976 to 2017). We selected 1976 as the beginning of our second study period because this is when global CO_2 concentrations and air temperatures started to rise sharply (Fig. 1). Our second objective was to determine if rangeland livestock grazing level (total animal units per year) and productivity as indicated by autumn calf numbers differed among decades and the two periods. An additional focus was the relationship between perennial plant cover (woody or herbaceous) and 1) livestock grazing levels of the entire state for the 1984 − 2017 period; or 2) cattle grazing levels in different counties of New Mexico for the 2000 − 2017 period. Several studies from different New Mexico range types have shown woody plant increase has adversely affected forage production and ecological condition over the past 100 yr (Buffington and Herbel, 1965; Howard et al., 1992; McDaniel et al., 1992; Herbel and Gibbens, 1996; Frost et al., 2007). In our interpretation of results, we also discuss socioeconomic and environmental factors (e.g., government policies, livestock prices, wars) that could have influenced rangeland livestock grazing levels and calf numbers in different time periods.

Our study provides basic knowledge on the magnitude and pace of past change in climate and perennial plant cover on New Mexico rangelands that will be helpful in quantifying future trends. We provide insight into how changes in climate and perennial plant cover may be associated with rangeland livestock production. This information will be useful to political leaders and natural resource managers in policy and land use decisions. It will help rangeland livestock producers in making decisions regarding grazing management, range improvement practices, enterprise diversification, enterprise size, selection of animal types, selection of livestock husbandry practices, and ranch capitalization.

Materials and Methods

Study Area

Our study area involved both the entire state of New Mexico (lat 34°18′25.7184″N, long 106°1′5.0376″W) and selected New Mexico counties (see later), all of which occur in the southwestern United States. New Mexico covers an area of ≈314 900 km^2. Roughly 92% of New Mexico is considered rangeland, and over 95% of this land is grazed by livestock (Gay et al., 1980). Landscape elevations and vegetation types across New Mexico show great variation (Gay et al., 1980). Elevations range from 866 m in southeastern New Mexico (northern end of the Red Bluff Reservoir on the Pecos River) to 4 011 m at Wheeler Peak (northcentral New Mexico's Sangre de Cristo Range, southern end of the Rocky Mountains). Few if any regions of the world exceed New Mexico in diversity of rangeland vegetation types. For this reason we consider it an especially useful indicator of how global warming could impact rangeland livestock production. Shortgrass prairie, midgrass prairie, tallgrass prairie, Chihuahua desert, salt desert, sagebrush grassland, chaparral (oak) woodland, pinyon juniper woodland, mountain browse, coniferous forest, and alpine grassland range types all occur in New Mexico (Gay et al., 1980). However, shortgrass prairie, pinyon juniper woodland, sagebrush grassland, and Chihuahua desert are the dominant types (Gay et al., 1980). Most of New Mexico has a bimodal precipitation pattern that typically involves a primary peak in summer, a lesser peak in winter, and dryness in the spring and autumn months (Gay et al., 1980; Holechek et al., 2011). Precipitation in the central and western parts of the state varies greatly over short distances

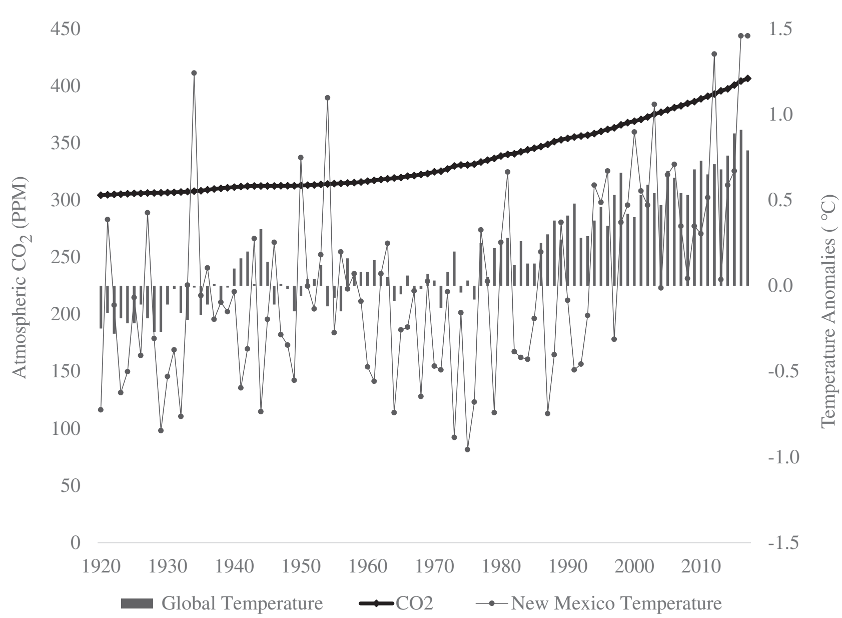

Figure 1. Global and New Mexico ambient air temperature anomalies (°C), and global CO_2 (ppm) between 1920 and 2017.

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due to sharp changes in elevation associated with landscapes dominated by mountains and valleys (Gay et al., 1980). The northeastern quarter of the state is relatively flat and has the plains climatic pattern (Gay et al., 1980; Holechek et al., 2011). The mean precipitation across New Mexico for our period of study (1920 − 2017) was 370 mm ranging from 175 in 1956 to 722 mm in 1941. In general, the climate of New Mexico is characterized by low relative humidity, abundant sunshine, four definite seasons, and peak precipitation in the summer months of July and August with a lesser peak in January.

Data Collection

Weather data for New Mexico were retrieved from the Western Regional Climate Center (WRCC, 2018). This center summarizes data collected from various locations across the state by the National Oceanic and Atmospheric Administration. Weather variables considered in our study included mean annual precipitation (mm) (MAP), mean annual air temperature (°C) (MAT), and Palmer Z drought severity index. Global air temperature anomalies (°C) and atmospheric CO_2 (ppm) data were retrieved from the National Oceanic and Atmospheric Administration (NOAA 2018a and 2018b).

The Palmer Drought Severity Index (PDSI) quantifies long-term drought using a combination of precipitation, air temperature, and soil moisture data (Karl, 1986). In contrast, short-term droughts are characterized by the Palmer Z drought index, which evaluates monthly moisture conditions with no memory of previous deficits or surpluses. This index can vary greatly from month to month unlike the PDSI in which antecedent conditions account for two-thirds of its value and is less sensitive to changes in the calibration periods (Karl, 1986). The Palmer Z drought index is considered more robust for identifying drought by using total water balance and soil data methodology.

Inventory data for beef cows, weaned calves, sheep, and horses were retrieved from US Department of Agriculture − National Agricultural Statistics Service databases (USDA-NASS, 2018) for the period of 1920 − 2017. Annual surveys sent to New Mexico farmers and ranchers are the basis for these data.

Remotely sensed vegetation data including shrub, tree, and perennial forb and grass cover were retrieved from the Rangeland Analysis Platform website (https://rangelands.app/data/; Jones et al., 2018) for the entire state of New Mexico and for 19 of 33 New Mexico counties. The Rangeland Analysis Platform (RAP) is an online tool that uses Google Earth Engine to combine historical (1984 − 2017) Landsat satellite data with topography and soils maps, as well as with data from 30 000 field plots scattered across the western United States. RAP models vegetation cover with a spatial resolution of 30 × 30 m. Therefore, at the state-scale, we plotted total AUs (see later) for New Mexico versus vegetation cover data for the entire time series (1984 − 2017) available through RAP. County-level analysis was conducted on a subset of 19 counties for which livestock inventory data were available. County-level livestock data in New Mexico include only cattle inventories for counties that comprise 90% of the New Mexico cattle population (n = 19). For county-level analyses we only used vegetation cover data for 2000 to 2017. Land cover data for this 17-yr period includes the use of at least two Landsat satellites; therefore, these data are deemed to have higher accuracy and coverage than those of the 1984 − 1999 period, which relied only on Landsat 5 imagery. We reasoned that analysis of rangeland vegetation cover of smaller areas (individual counties vs. the entire state of New Mexico) would require the highest levels of accuracy and coverage available to us.

We recognize that for some comparisons of climatic data, the median can be a better metric than the mean for describing normal (Thurow and Taylor, 1999). This can be the case in semiarid and arid areas where a few extremely abnormally wet or dry years can skew the arithmetic mean, so it is misleading of the central value. For our 98-yr precipitation data set, the median value (36.6 cm) was nearly the same as the mean (37.0 cm). Therefore, we consider the mean a good representation of the central value. This also applies to temperature data (median = 11.85°C, mean = 11.98°C). However, we do provide median and mean values in our tabular data sets.

Data Processing and Analysis

Livestock grazing levels (cattle, sheep, horses) were calculated in terms of animal units per year (AUY). The AUY is the standard unit used to equalize the grazing impact of different classes and kinds of livestock (1 AU = 450 kg) (Holechek et al., 2011). The national average beef cow and sheep weights for each year from the USDA-NASS (2018) database were used to adjust livestock weights to the standardized AU for calculating their additive grazing levels. Weights were not available for horses. Holechek et al. (2011) assigned horses on rangeland all year an AU factor of 1.8 because of their higher weight than adult cattle and more feed consumption per unit body weight than ruminants. However, we recognize part of the horse category did not involve adults and ranch horses typically receive some level of harvested feed and/or nonrange pasturage during the year; therefore, we used 1.25 as suggested by Vallentine (2001) to convert horse numbers to AUs. The overall grazing level for each year was derived by adding the calculated AUs for cattle, sheep, and horses.

In order to obtain an index that can be used to relate climate to rangeland stocking intensity, we divided total livestock AU for each year by the total rangeland area in square kilometers. We refer to this number divided by the cm of precipitation for each year as a stocking index. Our basic premise is that a decrease in the stocking index through time reflects a declining relation between precipitation levels and stocking intensity (i.e., progressively higher precipitation is needed to maintain similar levels of stocking intensity) while an increase reflects the opposite. In a general sense, we assume livestock grazing levels for each year reflect rangeland livestock carrying capacity, acknowledging that in some years New Mexico's rangelands were overstocked and other years understocked. However, on a decade basis and for the two time periods we consider rangeland livestock levels to be a reasonable indicator of carrying capacity. Calf numbers are the total number of weaned beef calves in ranch inventories in the autumn of each year. We used this as our indicator of saleable livestock productivity (offtake), recognizing combined weights of marketed calves, heifers, steers, and culled cows would be a more accurate metric. However, this information was not available to us.

Climate and livestock data were analyzed using SAS 9.4 (SAS Institute, 2013). The *PROC MEANS* procedure was used to calculate the descriptive statistics (mean and standard error) for grazing level, stocking index, calf numbers, mean annual precipitation, mean annual air temperature, and Palmer Z drought index for each decade (1920s to 2010s) and the two study periods (1920 − 1975 and 1976 − 2017). *PROC UNIVARIATE* in SAS 9.4 (SAS Institute, 2013) was used to test the normality for grazing level, stocking index, calf numbers, mean annual precipitation, mean annual air temperature, and Palmer Z drought index for the two study periods (1920 − 1975 and 1976 − 2017). No variable was found to be normally distributed. Accordingly, *PROC NPARIWAY* in SAS 9.4 (SAS Institute, 2013) was used to investigate the median difference between the two periods (1920 − 1975 and 1976 − 2017) using the Mann–Whitney U-test at $P \le 0.05$ level. The nature of the relationships among grazing level and mean annual precipitation (mm), mean annual air temperature (°C), and Palmer Z drought index was analyzed using the *PROC CORR* procedure.

At the level of the entire state of New Mexico, *PROC AUTOREG* in SAS 9.4 (SAS Institute, 2013) was used to analyze trends in cover of woody (trees + shrubs) and herbaceous (perennial forbs and grasses) vegetation, as well as the relationship between livestock AUs and vegetation cover dynamics for the 1984–2017 period. We used General Durbin Watson (DW) statistic to diagnose 1st to 10th order autocorrelation and the Portmanteau Test statistic to diagnose heteroscedasticity. When autocorrelation and heteroscedasticity were detected, Generalized Autoregressive Conditional Heteroscedasticity (GARCH) or

Exponential GARCH models were used. County-level vegetation data including shrub, tree, and perennial forb and grass cover were averaged for the first 3 yr (2000 − 2002) and last 3 yr (2015 − 2017) of the time series to determine if there had been woody plant encroachment and a decrease in herbaceous cover, which usually includes the bulk of livestock forage species. Paired Student's *t* tests were used to compare county-level vegetation cover means for the 2000 − 2002 versus 2015 − 2017 periods using *PROC TTEST* in SAS 9.4 (SAS Institute, 2013).

Results and Discussion

Precipitation, Air Temperature, and Palmer Z Drought Severity Index

Precipitation (MAP) and air temperature (MAT) differed ($P \le 0.05$) between period 1 (1920 − 1975) and period 2 (1976 − 2017), but no difference occurred for the Palmer Z drought severity index (Table 1). Precipitation in period 2 was 9.6% higher than that in period 1. This difference is explained primarily by 2 decades: the 1950s in period 1, which were abnormally dry, and the 1980s in period 2, which were abnormally wet (see Table 1). In the 1980s and 1950s, precipitation was 12% above and 16% below the long-term average, respectively. We define a dry or wet period as either ≥ 3 consecutive yr of below- or above-average precipitation with overall departure 10% or more from the long-term average broken by ≥ 2 consecutive yr with above- or below-average precipitation. Under this condition the dry or wet period is not considered to be broken if a 1-yr exception occurs within the period, as is typical of extended wet or dry periods. On this basis three distinct dry periods occurred within our data set (1945 − 1956, 2000 − 2003, 2011 − 2013). Recently (2000 − 2017), overall precipitation has been slightly below (98%) the long-term average with two distinct dry periods (see Table 1). The harshest period of below-average precipitation in our data set occurred from 1945 to 1956 with 78% of the long-term average (37.0 cm). In this dry period, only 1 yr (1949) had above-average precipitation. In the 2000 through 2003 dry period, precipitation in all 4 yr was below average with 84% of the mean. In 2011 through 2013, all yr had below-average precipitation with 75% of the mean. Three of the 10 driest yr occurred in the 1950s: one in the 1930s, one in the 2000s, and two in the 2010s (Table 2).

We recognize there are different ways to assess drought severity. The Society for Range Management (1989) defines drought as prolonged dry weather when precipitation is generally < 75% of the average annual amount. On this basis, 10 drought yr occurred in our 98-yr study period with eight in the first period (1922, 1924, 1934, 1945, 1947, 1950, 1951, 1953, 1956, and 1964) and only three in the second period (2003, 2011, and 2012). In general, the Palmer Z drought severity index is consistent in showing this same set of years to involve the harshest droughts (see Table 2). Palmer Z drought severity index values further confirm the 1950s' dry period was the harshest followed by the 2010s' and 2000s' drought.

Five distinct wet periods occurred in our study (1940 − 1942, 1957 − 1961, 1978 − 1999, 2004 − 2010, and 2014 − 2017). The 1978 through 1999 interval stands out because it lasted 22 yr and had only 3 yr of below-average precipitation (1980, 1989, and 1995). During this period, precipitation was 12% above the long-term average. Eight of the 10 wettest yr in our study occurred in period 2, with 3 in the 1980s (see Table 2). We consider the 1978 through 1999 wet period to be the most unusual aberration in our study. Its occurrence was generalized across the southwestern United States (Seager and Vecchi,

Table 1
Comparison of New Mexico grazing level (AUY), stocking index (AU/km^2/cm), calf numbers, mean annual precipitation (cm), mean annual air temperature (°C), and Palmer Z Drought Index by decade (1920s-2010s) and periods (1920-1975 and 1976-2017).

Decade		Grazing level (AUY)	Stocking index (AU/km^2/cm)	Calf no.	Precipitation (cm)	Temperature (°C)	Palmer Z Drought Index
1920s	Mean	1 033 519	0.100	337 300	36.98	11.70	−0.04
	Median	1 015 012	0.100	310 500	37.21	11.62	−0.17
	SE	32 947	0.009	18 667	2.28	0.14	0.23
1930s	Mean	1 009 971	0.099	290 200	36.12	11.90	−0.05
	Median	1 000 149	0.095	281 500	35.75	11.86	−0.15
	SE	18 714	0.007	11 339	1.80	0.17	0.26
1940s	Mean	928 326	0.091	285 500	37.85	11.72	0.37
	Median	967 894	0.090	287 000	35.54	11.66	0.13
	SE	27 613	0.007	6 428	4.16	0.11	0.52
1950s	Mean	820 959	0.099	283 100	30.90	12.16	−0.77
	Median	826 785	0.100	282 000	29.68	12.02	−1.02
	SE	11 467	0.010	5 763	2.56	0.13	0.29
1960s	Mean	863 205	0.085	328 000	35.54	11.72	−0.17
	Median	862 741	0.085	307 500	34.54	11.73	−0.05
	SE	11 296	0.005	14 894	1.70	0.11	0.17
1970s	Mean	804 921	0.079	451 100	36.32	11.57	0.04
	Median	797 617	0.080	443 000	35.52	11.50	0.04
	SE	10 036	0.004	10 503	1.76	0.14	0.20
1980s	Mean	748 067	0.064	340 700	41.76	11.87	0.52
	Median	739 523	0.060	343 000	41.00	11.69	0.69
	SE	10 320	0.004	16 611	2.30	0.14	0.29
1990s	Mean	772 467	0.065	267 800	41.25	12.09	0.23
	Median	776 082	0.070	261 500	39.70	12.12	0.23
	SE	4804	0.003	3 530	1.78	0.14	0.24
2000s	Mean	707 890	0.071	236 500	36.15	12.49	−0.45
	Median	704 141	0.075	230 000	36.60	12.49	−0.33
	SE	14 123	0.004	11 305	2.03	0.11	0.22
2010s	Mean	675 140	0.069	201 250	36.75	12.78	−0.63
	Median	681 875	0.060	192 500	37.05	12.61	−0.66
	SE	15 428	0.008	6 731	3.40	0.20	0.34
Period 1 (1920-1975)	Mean	919 603	0.09	318 875	35.52	11.8	−0.11
	Median	**900 409^{A}**	**0.090^{A}**	**299 000^{A}**	**35.04^{B}**	**11.80^{B}**	**−0.19^{A}**
	SE	14 216	0.003	7 879	1.09	0.06	0.13
Period 2 (1976-2017)	Mean	733 251	0.07	284 643	38.90	12.23	−0.04
	Median	**739 560^{B}**	**0.065^{B}**	**261 500^{B}**	**39.24^{A}**	**12.32^{A}**	**−0.19^{A}**
	SE	7 701	0.002	13 193	1.12	0.09	0.14

AU/km^2/cm indicates animal unit per square km per 1 cm precipitation.
$^{A-B}$Median within the same column that have different superscripts differ ($P \le 0.05$).

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Table 2
New Mexico grazing level (AUY), stocking index (AU/km^2/cm), calf numbers, mean annual precipitation (cm), mean annual air temperature (°C), and Palmer Z Drought Index for the top 10 wettest, driest, hottest, and coldest yr for the 1920-2017 period.

	Period	Yr	Grazing level (AUY)	Stocking index (AU/km^2/cm)	Calf no.	Precipitation (cm)	Temperature (°C)	Palmer Z Drought Index
Wettest	1	1923	1 025 864	0.074	365 000	47.70	11.36	0.95
	1	1931	989 512	0.072	277 000	47.27	11.61	1.38
	1	1941	1 002 631	0.048	255 000	72.24	11.38	4.52
	2	1984	750 900	0.055	314 000	46.89	11.55	0.91
	2	1985	739 046	0.053	346 000	47.88	11.79	1.79
	2	1986	725 527	0.046	340 000	54.76	12.18	1.34
	2	1991	778 042	0.053	262 000	50.55	11.49	1.3
	2	1997	774 122	0.054	280 000	49.76	11.67	0.87
	2	2004	648 013	0.047	230 000	47.35	11.97	0.52
	2	2015	628 622	0.041	205 000	53.01	12.65	0.87
	Mean		**806 228**	**0.054**	**287 400**	**51.7**	**12**	**1.45**
Driest	1	1922	1 145 601	0.153	444 000	25.91	11.87	−1.23
	1	1924	1 008 713	0.136	315 000	25.55	11.48	−0.29
	1	1934	1 110 189	0.152	366 000	25.22	13.22	−1.82
	1	1945	961 790	0.129	311 000	25.68	11.78	−0.96
	1	1951	853 636	0.113	315 000	26.19	11.98	−1.17
	1	1953	833 873	0.113	303 000	25.43	12.16	−1.16
	1	1956	847 425	0.167	296 000	17.48	12.18	−2.05
	2	2003	658 584	0.091	245 000	25.04	13.04	−1.66
	2	2011	716 057	0.093	225 000	26.44	12.49	−1.7
	2	2012	683 099	0.108	190 000	21.82	13.33	−1.91
	Mean		**881 896**	**0.126**	**301 000**	**24.5**	**12**	**−1.40**
Hottest	1	1934	1 110 189	0.152	366 000	25.22	13.22	−1.82
	1	1950	844 966	0.105	289 000	27.74	12.73	−1.3
	1	1954	815 928	0.096	286 000	29.34	13.08	−1.42
	2	1996	761 264	0.069	260 000	38.02	12.65	−0.77
	2	2000	781 893	0.076	300 000	35.66	12.88	−0.89
	2	2003	658 584	0.091	245 000	25.04	13.04	−1.66
	2	2006	699 483	0.056	220 000	42.77	12.69	−0.44
	2	2012	683 099	0.108	190 000	21.82	13.33	−1.91
	2	2016	639 046	0.059	185 000	37.14	13.44	−0.78
	2	2017	700 904	0.056	185 000	43.03	13.44	−0.4
	Mean		**769 535**	**0.087**	**252 600**	**32.6**	**13**	**−1.14**
Coldest	1	1920	1 205 290	0.115	349 000	36.22	11.26	0.42
	1	1929	894 120	0.075	285 000	41.33	11.13	0.51
	1	1932	1 031 460	0.087	285 000	41.05	11.22	0.92
	1	1944	987 312	0.092	320 000	36.88	11.24	0.25
	1	1964	927 295	0.119	304 000	26.98	11.24	−0.95
	1	1973	845 889	0.091	473 000	32.16	11.09	0.74
	1	1975	858 875	0.085	459 000	34.75	11.02	0.46
	2	1976	786 225	0.090	509 000	30.12	11.30	−0.77
	2	1979	770 577	0.068	480 000	39.19	11.24	1.06
	2	1987	708 616	0.060	323 000	41.10	11.23	1.51
	Mean		**901 566**	**0.088**	**378 700**	**36.0**	**11**	**0.42**

AU/km^2/cm indicates animal unit per square km per 1 cm precipitation.

2010). Paleoclimatic data based on tree rings indicates it to be a rare event occurring once in a thousand years (Layzell and Evans, 2014). Unfortunately, political leaders and planners have assumed this extremely favorable condition to be common within 100-yr cycles with regard to water resources (Fishman, 2011; Allhands, 2018). This assumption is now leading to disaster as the precipitation pattern returns to normalcy and global warming intensifies. Large cities such as Las Vegas, Phoenix, Tucson, Albuquerque, and Los Angeles are increasingly confronting water scarcity as their populations grow but fresh water supplies dwindle (Fishman, 2011; Allhands, 2018).

MAT in period 2 (12.2°C) was 3.4% higher than in period 1 (11.8°C) (see Table 1). We note that 2016 and 2017 were the hottest yr recorded for New Mexico and 7 of the 10 hottest yr occurred between 1990 and 2017. In contrast, 1975 was the coldest recorded yr (11.02°C) with 7 of the 10 coldest yr occurring in period 1 (see Table 1). We are establishing 12.0°C as the threshold MAT between cool and warm yr with yr of 13°C or higher considered to be hot. Yr below 12.0°C heavily dominated (67%) up to 1993, but afterward only 1997 was below this threshold. Only 2 yr (1934 and 1954) were hot (above 13.0°C) in the first study period, but 4 hot yr (2003, 2012, 2016, and 2017) occurred in the second period. Air temperatures in the last 6 yr of our study averaged 0.55°C higher than the previous 6 yr (12.90°C vs. 12.35°C). This indicates a strong acceleration of the warming trend. New Mexico's climatic data are consistent with global data in showing a definite upward trend in air temperatures since the 1970s with an acceleration over the last 6 yr (see Fig. 1) (USGCRP, 2017; Dillon, 2018; WMO, 2018).

Studies evaluating the 1950s drought across the entire Great Plains have found it to be the most severe drought that has occurred within the past 100 yr (McGregor, 2013; Layzell and Evans, 2014; Heim, 2017). In general, these studies found the 1950s drought was shorter in overall duration but more intense over a larger area for a longer period than the 1930s drought. Our findings from NM are in agreement with Heim (2017) that droughts in the present period (2003, 2011, 2012) are characterized by warmer air temperatures than those of the 1930s and 1950s. MAT for the 3 drought yr in period 2 of our study averaged 12.93°C compared with 12.03°C for the 10 yr in period 1. Heim (2017) noted that although the recent droughts may not be the result of climate change, the increased air temperatures of these droughts accentuates their adverse impacts on agriculture. Paleoclimatic data indicate that droughts similar to the 1930s have occurred in the southern Great Plains region three to four times per century with a 35% chance of severe drought in any decade (Layzell and Evans, 2014). Several megadroughts lasting > 20 yr occurred from 850 to 1500 AD (known as the *Medieval Warm Period*). The longest of these droughts spanned 110 yr (1317 − 1427 AD). From about 1500 − 1850 AD (a period commonly referred to as "the little ice age") a cooling trend occurred in

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which droughts became shorter in duration. On the basis of this long-term climatic history it seems probable that megadroughts will occur again regardless of whether the climate becomes warmer. On the other hand, we note that only 3 drought yr occurred in our second study period compared with 10 in the first one. In studying New Mexico's climatic history, we find temporal spacing of both dry and wet periods to be somewhat unpredictable. In general, dry periods lasting about 5 yr occur after 9 near-average to above-average yr, but there is much deviation from this generalization. On the basis of the consideration of our data and the literature, we conclude the future frequency, duration, and intensity of droughts in New Mexico is highly uncertain. We refer the readers to Seager and Vecchi (2010) and Polley et al. (2013) for comprehensive considerations of recent and future climatic trends on rangeland in the southwest and other parts of the United States.

Grazing Level, Calf Numbers, and Stocking Index

Both grazing level and calf numbers were lower ($P \le 0.05$) in period 2 than period 1 (see Table 1). Declines of 20% and 11% occurred between the two periods for grazing level and calf numbers, respectively. We note that a shift occurred to more cattle and fewer sheep and horses in period 2 compared with period 1 (Fig. 2). Most of this shift was in the 1960s when cattle AUs went from 67% to 82% of the grazing level (see Table 1). Horse AUs sharply declined between the 1950s and 1960s (14% to 6% of grazing level), while sheep AUs gradually declined between the 1950s and 2010s (19% to 2% of grazing level) (see Table 1). Although we cannot fully explain these shifts, we believe the decline in horse grazing levels is mostly due to increased use of vehicles in daily ranch operations in terms of livestock gathering and handling. In regard to sheep, we believe lower predation problems and fewer labor requirements associated with cattle explain the switch.

In Texas, Wilcox et al. (2012) found the same downward trend over time regarding rangeland livestock grazing levels as in our study. The same switch from sheep to cattle documented in our study has occurred in Texas (Wilcox et al., 2012). In Texas, sheep and goat numbers peaked in the 1940s, when wool was a strategic commodity. Price supports for wool were implemented in 1938 but phased out in the 1990s (Wilcox et al., 2012). Demand for wool also dropped because of development of synthetic fibers and competition from abroad.

Grazing level and calf numbers were not correlated ($P > 0.05$) with precipitation or the Palmer Z severity drought index in either period of study or for both periods of study combined (Figs. 3 and 4). However, grazing level and calf numbers were correlated ($P \le 0.05$) with air temperature in the 1976 – 2017 period ($r = -0.40$) and in both periods combined ($r = -0.34$). A strong divergence for both grazing level and calf numbers with air temperature began in the 1990s (see Figs. 3 and 4). We believe the declining grazing levels and calf numbers in the second period may be explained in part by global warming adversely affecting forage production, which we discuss later.

Our stocking index as estimated by AUY/km^2/cm of precipitation was 28% lower ($P \le 0.05$) in period 2 than period 1 (see Table 1). Although not well related to air temperature, stocking index was negatively correlated ($P \le 0.05$) with the Palmer Z drought severity index for both study periods ($r = -0.69$ period 1, $r = -0.79$ period 2) and data combined ($r = -0.61$) (Fig. 5). Paradoxically, the stocking index was lowest in wet yr and highest in dry yr, likely due to known time lags in the typical drought destocking and postdrought restocking cycles. Our stocking index indicates overall that a centimeter of precipitation is currently less effective in terms of generating forage growth than 40 yr ago. Forage production data collected since 1968 on the Chihuahuan Desert Rangeland Research Center near Las Cruces in southcentral NM have shown a downward trend since 1993, even though precipitation has been above average. (Khumalo and Holechek, 2005; Sawalhah, 2014; Thomas et al., 2015; McIntosh et al., 2019). Forage production has been suppressed (less than half the long-term average) in years with abnormally hot summers, even when total annual and summer growing season precipitation were near or above average (McIntosh et al., 2019). This same situation has also been observed on 20 long-term monitoring sites distributed across mountain grassland,

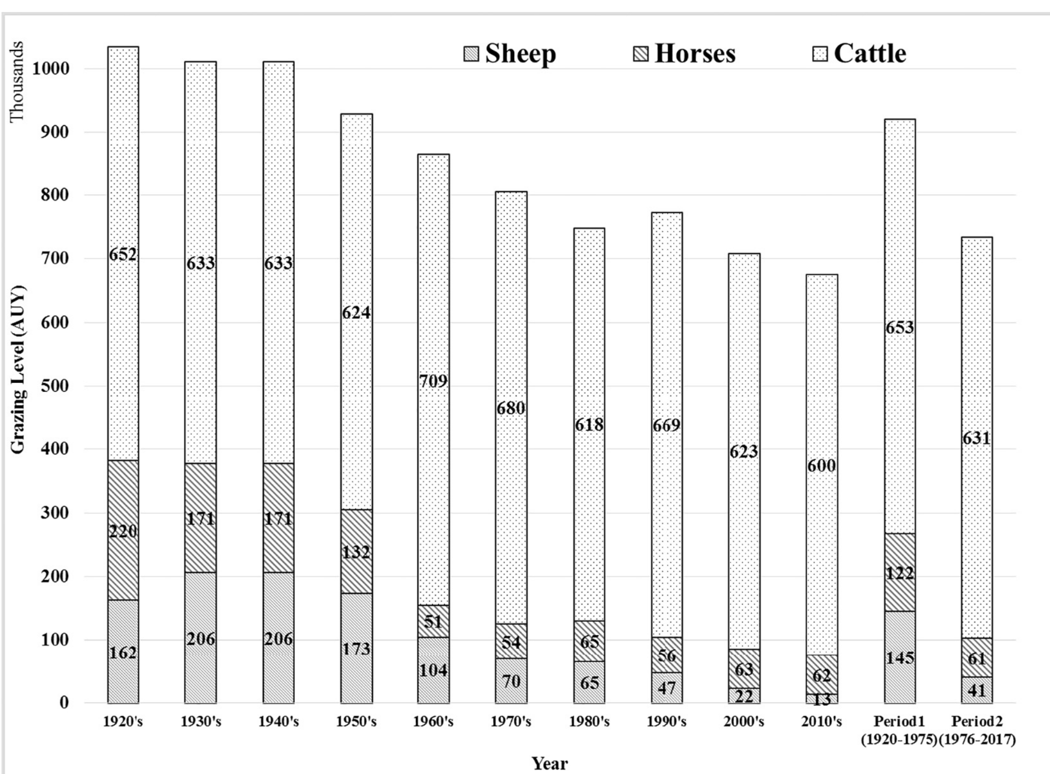

Figure 2. New Mexico grazing level (AUY) for different livestock species by decade (1920s to 2010s) and periods of analysis (1920 – 1975, 1976 – 2017).

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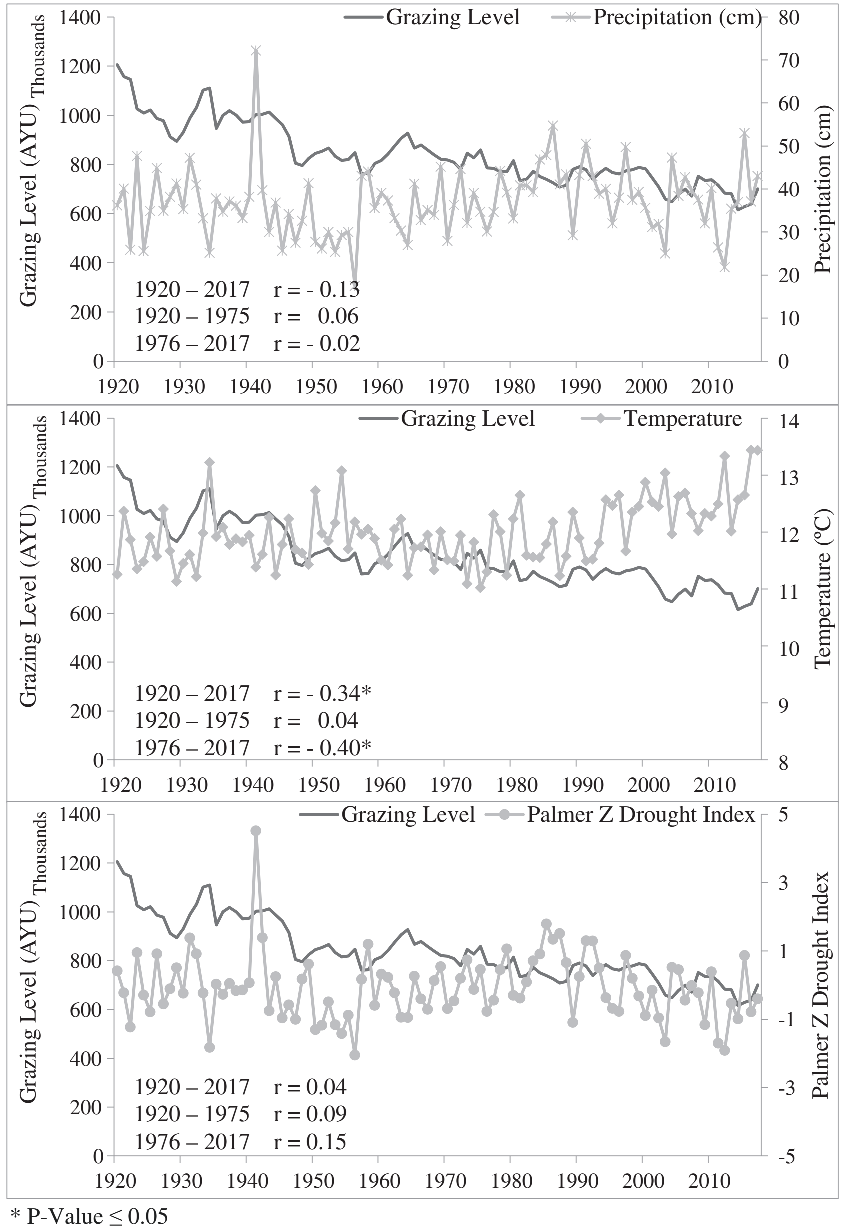

Figure 3. Relationship between grazing level (AUY) and mean annual precipitation (cm), mean annual temperature (°C), and Palmer Z drought index for the 1920 − 2017 period in New Mexico.

mountain browse, and sagebrush grassland range types near Dulce in northcentral New Mexico (Galt and Holechek, 2017).

In the 1970s, when agronomists began studying climate change impacts on grain yields (corn, wheat, rice, and sorghum), it was believed the overall effect would be neutral. The theory was that yield boosts due to higher photosynthesis from more CO_2 in the atmosphere would offset the impacts of increased heat stress on plant physiology and higher evaporation of soil moisture (Bourne, 2015). Actual research has shown that initially more CO_2 does boost grain yields, but as temperatures increase this positive effect is more than offset by stress from heat waves that adversely affect plant metabolism (Asseng et al., 2011; Challinor et al., 2014; Derying et al., 2014). As with grain crops, it appears that stress from heat waves can depress yields of rangeland forage grasses, but this needs more study. The metabolism of plant species endemic to an area is typically disrupted when extreme air temperature aberrations occur outside their range of adaptation (Hatfield and Prueger, 2015). Even mild temperature aberrations can adversely affect photosynthesis, while those that are extended and extreme can cause plant mortality.

Change in Plant Cover and Livestock Animal Units

Our state-level analysis showed no clear trend in woody plant cover ($P = 0.06$) or herbaceous cover ($P = 0.28$) over the 33-yr period analyzed (Fig. 6). Over this time period, woody plant versus herbaceous cover dynamics across the state of NM were not significantly correlated ($P = 0.32$). Livestock AU trends at the state level were not related to woody plant cover variation ($P = 0.11$) but were significantly associated with herbaceous cover dynamics ($r = 0.37$, $P \le 0.05$), particularly after the late 1990s (see Fig. 6), coinciding with the termination of the emergency drought feed program (Fig. 7).

County-level analysis, however, suggested that declining cattle inventories were associated with woody plant cover dynamics during the 2000 − 2017 period. Across 19 counties, average woody plant cover increased 1.91% (20.17%−22.08%) between 2000 − 2002 and 2015 − 2017 ($P \le 0.05$) (Table 3). In this period, significant ($P \le 0.05$) woody plant cover increases occurred in 10 of the 19 counties. None of the counties had a significant decrease ($P > 0.05$) in woody plant

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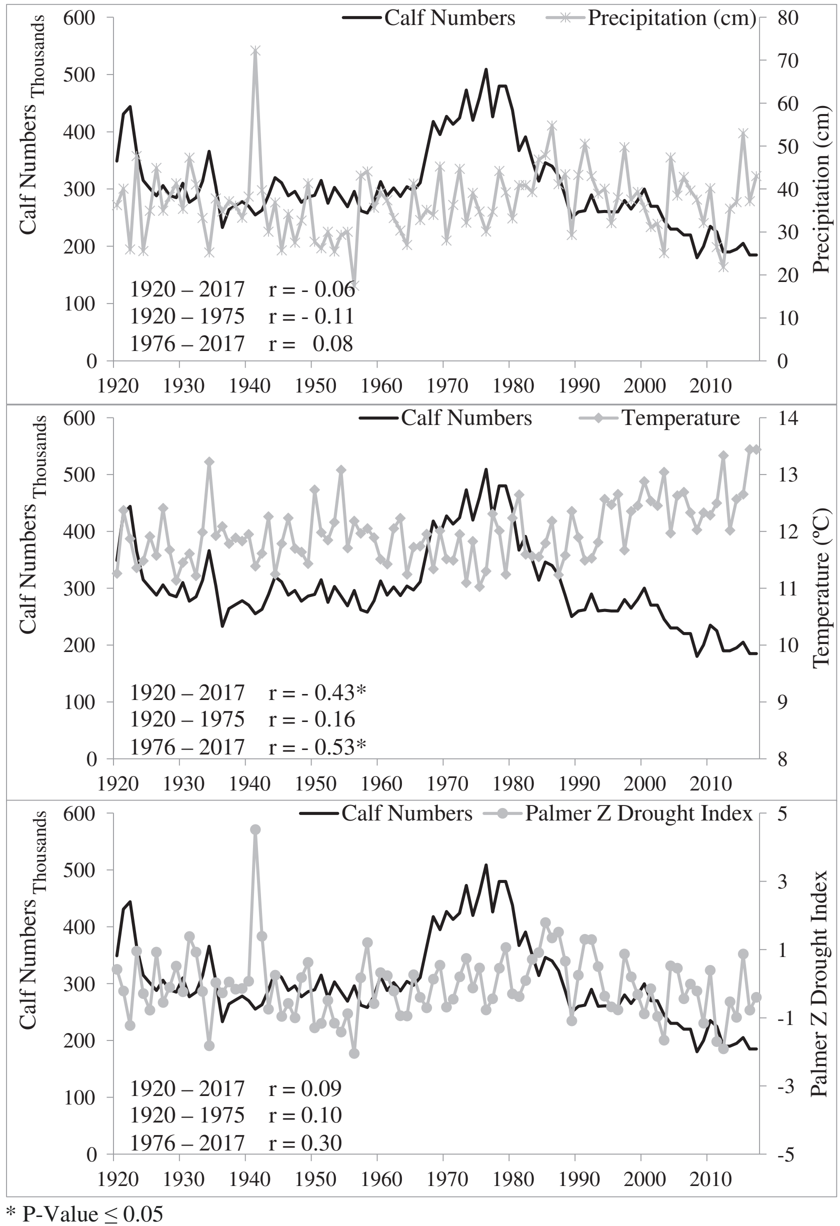

Figure 4. Relationship between calf numbers and mean annual precipitation (cm), mean annual temperature (°C), and Palmer Z drought index for the 1920 — 2017 period in New Mexico.

cover. Eastern New Mexico counties had larger woody plant increases than western New Mexico counties (3.83% vs. 0.53%, respectively). The largest increases (3 — 6%) occurred in Lea, Eddy, Chaves, and Roosevelt counties in southeastern New Mexico.

We believe the lower increase in woody plant cover in western than eastern New Mexico during the 2000 — 2017 period may be explained by more burning (both prescribed and unplanned) and higher application of government-sponsored rangeland improvement projects in the western half of New Mexico. The Bureau of Land Management (BLM), Forest Service, and tribal lands dominate western New Mexico, while privately owned lands predominate in eastern New Mexico. Grassland landscapes dominate eastern New Mexico (16% woody plant cover) with shrub and tree landscapes (25% woody plant cover) most common in western New Mexico. Since 2000, large-scale woody plant control by fire, herbicides, and mechanical methods have occurred on millions of hectares of BLM, Forest Service, and tribal lands in western New Mexico, although we could not find specific figures on areas at the county or state level. The lower levels of woody plants coupled with less need and government funding for their control may explain why they increased more in eastern New Mexico. We point out the need for additional information regarding annual amount of area in different counties with woody plant control. Assessment of the financial effectiveness of these programs in terms of enhancing livestock production, wildlife habitat, and ecosystem services (especially watershed health) would be highly useful to producers, stakeholders, government administrators, and politicians.

In the period 2000 — 2002 to 2015 — 2017 the overall NM livestock grazing level decreased 12% with cattle AUs decreasing 9% for the 19 counties we evaluated for woody plant increase. In four counties cattle AUs declined, while in six counties they increased ($P \leq 0.05$). In the western New Mexico counties where woody plant cover increased only 0.5%, cattle AUs increased 9.5%. In contrast, cattle AUs decreased 23% across the eastern counties, which had a 3.8% increase in woody plant cover. The higher level of woody plant control in western New Mexico we have previously discussed may have played an important role in the increased cattle AUs in western New Mexico. This, however, needs further evaluation.

Our county-level analyses showed a combined perennial grass and forb cover increase of 3.2% (28.8 — 32.0%) between 2000 — 2002 and

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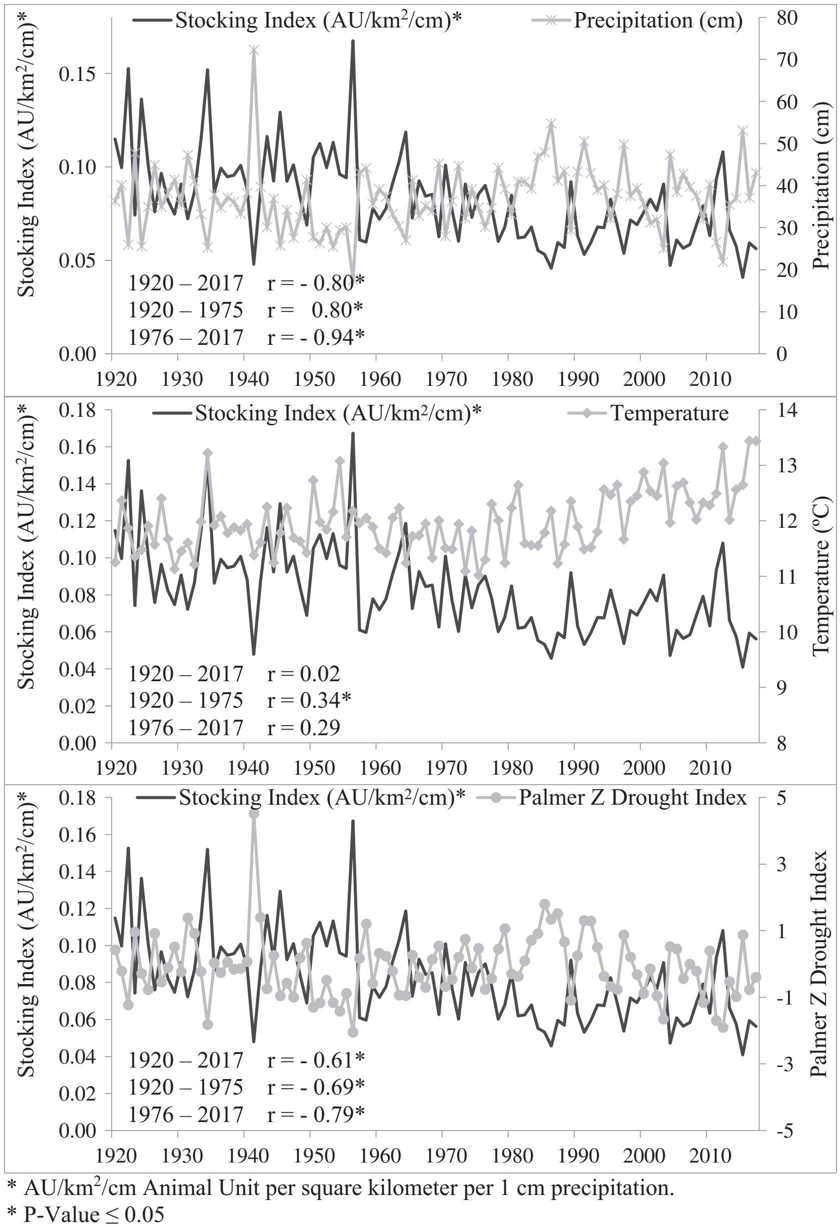
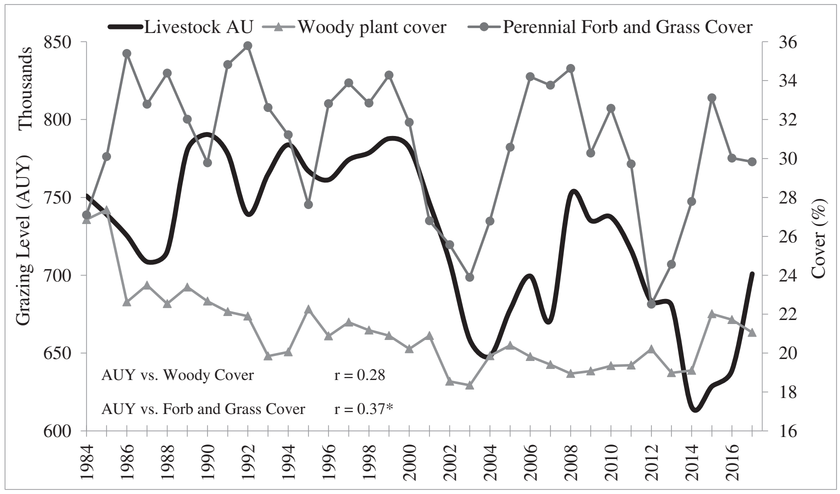


Figure 5. Relationship between stocking index (AU/km^2/cm) and mean annual precipitation (cm), mean annual temperature (°C), and Palmer Z drought index for the 1920 – 2017 period in New Mexico.

2015 – 2017 ($P \leq 0.05$). This may be explained by precipitation during the last 3 yr of our study, which was 20% above the long-term average compared with 11% below-average precipitation in the 2000 – 2002 period. Perennial grass and forb cover levels increased more in eastern (5.9%) than western (1.2%) New Mexico counties. Because botanical composition is not available for the perennial grass and forb component, it is uncertain how rangeland ecological condition and carrying capacity may have been influenced by the increase in their combined cover. Research in southcentral New Mexico by Gherardi and Sala (2015) and McIntosh et al. (2019) indicates under conditions of more erratic annual precipitation and global warming, forbs and shrubs can thrive while perennial grasses languish.

An important limitation of the vegetation cover data we have discussed is that it does not account for individual plant species. Broom snakeweed (*Gutierrezia sarothrae* [Pursh] Britton & Rusby) is a low-growing, toxic, short-lived, perennial half-shrub that has invaded large rangeland areas across New Mexico (Gay et al., 1980; Pieper and McDaniel, 1990). It is a formidable competitor when growing in association with perennial grasses that can completely dominate vegetation composition (Pieper and McDaniel, 1990). Broom snakeweed is a component of the woody plant cover in the remote sensing we have used. The cover of broom snakeweed can vary greatly among years as its density is affected by both timing and amount of annual precipitation (Pieper and McDaniel, 1990). Above-average winter precipitation generally favors broom snakeweed. In general, broom snakeweed is a bigger problem on eastern than western New Mexico rangelands (Pieper and McDaniel, 1990). The higher level of woody plant increase on eastern than western NM rangelands may be in part explained by broom snakeweed.

Several studies on different range types in New Mexico have documented woody plant increases and associated loss of forage production (Buffington and Herbel, 1965; Howard et al., 1992; McDaniel et al., 1992; Herbel and Gibbens, 1996; Frost et al., 2007). The encroachment of woody plants into grasslands and thickening of woody plant cover in savanna and forest areas in New Mexico and other western states since the early 1900s has been well documented (Scifres, 1980;



* P-Value ≤ 0.05

Figure 6. Relationship between grazing level (AUY) and vegetation cover (%) for the 1984—2017 period in New Mexico.

Vallentine, 1989; Archer, 1994; Van Auken, 2000; Barger et al., 2011; Anadon et al., 2014). Actual rates of woody plant encroachment have varied greatly by range type and through time (Archer, 1994). In general, woody plant invasion is accelerated by severe extended droughts such as in the 1950s and retarded by lengthy wet periods such as in the 1980s and 1990s with some exceptions (Archer, 1994; Holechek et al., 2011). Annual increase rates in woody cover on southwestern US rangelands are estimated to vary from 0.5% to 2.0% depending on the vegetation type, soil, and climatic situation (Anadon et al., 2014). Every 1% increase in woody plant cover can reduce forage production by ≥ 2% due to competition for moisture and nutrients, shading, and chemical inhibition. Drivers of woody plant invasion include excessive grazing by livestock and wildlife, altered fire regimes, seed dispersal by livestock and wildlife, extended drought, and elevated CO_2 levels (Van Auken, 2000; Barger et al., 2011; Anadon et al., 2014).

In theory, rising levels of atmospheric CO_2 favor woody plants because most of them have the C3 photosynthetic pathway while dominant native warm season range grasses have the C4 pathway (Van

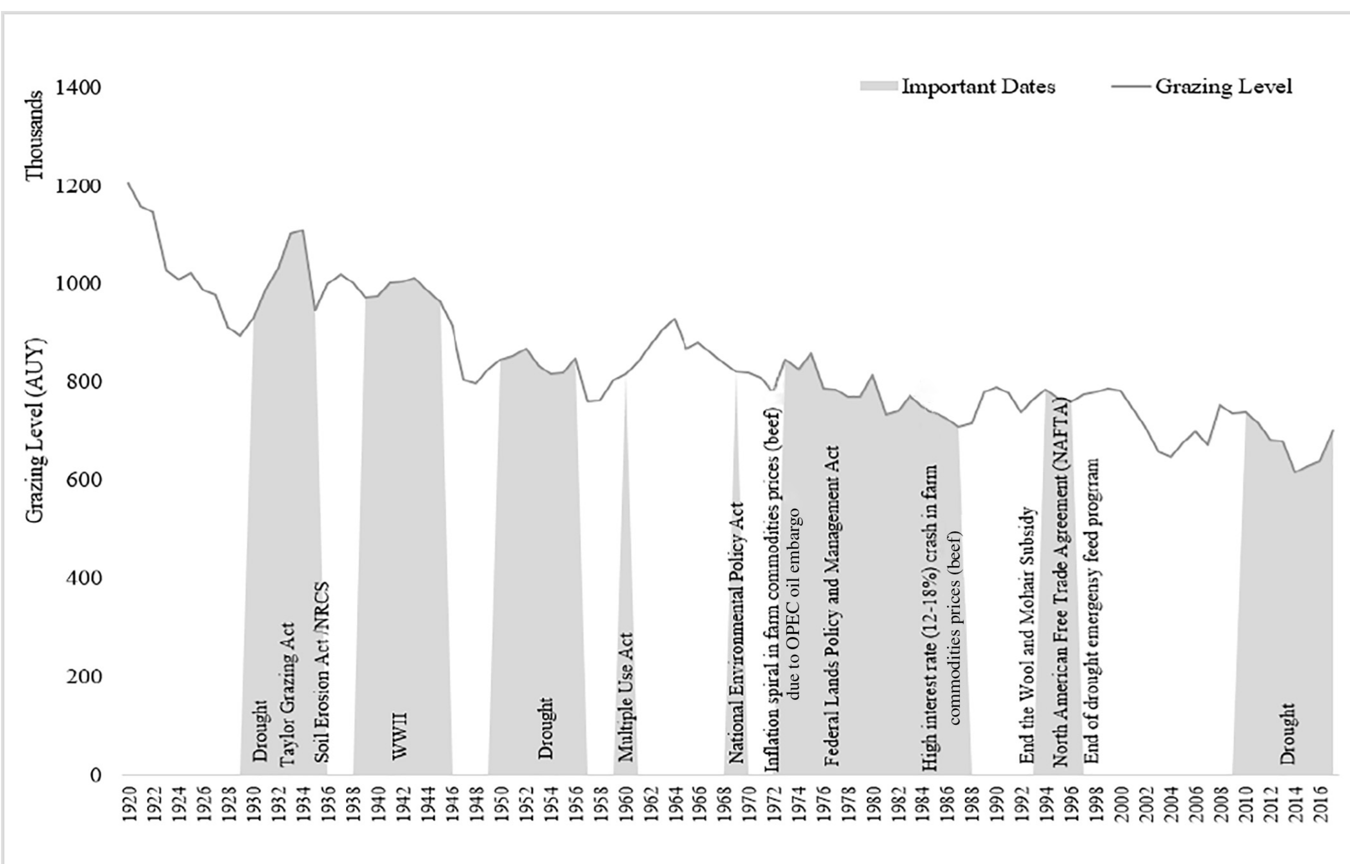


Figure 7. Relationship between grazing level (AUY), drought, and political/economic events for the 1920—2017 period in New Mexico.

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Table 3
New Mexico selected counties cattle animal units (AU) and Landsat-derived estimates of vegetation cover (%) change over time.

	Average woody cover			Perennial grass and forb cover			Cattle animal units		
NM county	2000-2002	2015-2017	*t*	2000-2002	2015-2017	*t*	2000-2002	2015-2017	*t*
Catron	34.65	33.14	−1.5	26.48	26.19	−0.41	22 591.7	21 618.2	−0.67
Chaves	10.3	15.01	4.42[1]	33.45	36.8	2.4	39 425	36 483.7	−0.93
Colfax	25.06	27.63	6.46[1]	45.14	48.87	1.21	27 543.7	14 638.5	−147.67
Curry	11.34	13.1	2.4	44.71	50.15	3.14[1]	18 872.7	10 876.9	−3.39[1]
Doña Ana	16.55	18.15	8.53[1]	15.91	16.7	0.46	8 213.3	10 469.3	3.12[1]
Eddy	12.81	18.89	13.94[1]	23.83	30.99	3.74[1]	26 290.7	22 524.3	−2.48
Grant	28.81	29.39	0.64	26.4	26.24	−0.13	26 897.2	23 929.3	−1.37
Harding	8.92	11.82	4.58[1]	43.59	51.96	3.12[1]	27 106	16 179.9	−6.91[1]
Lea	10.19	16.29	6.68[1]	31.01	40.49	12.1[1]	33 291	27 011.4	−8.31[1]
McKinley	18.56	17.85	−0.68	18.63	21.6	2.24	19 320	25 198.8	7.89[1]
Otero	22.95	23.99	8.00[1]	21.33	23.53	1.97	16 427.3	14 639	−1.33
Rio Arriba	33.51	35.69	2.53	22.72	23.24	6.20[1]	18 495	23 657.3	6.48[1]
Roosevelt	10.19	13.46	4.49[1]	43.56	50.24	4.63[1]	20 125.7	18 173.6	−1.42
Sandoval	23.34	23.11	−0.25	20.52	22.97	8.64[1]	12 330	14 140	3.79[1]
San Miguel	23.52	26.75	6.82[1]	35.15	38.24	1.18	32 863	28 007.6	−2.36
Santa Fe	25.49	26.12	0.44	23.92	25.44	3.14[1]	8 422.2	5 347.7	−8.28[1]
Socorro	17.67	18.28	0.68	23.73	23.45	−0.39	21 974.8	23 249.8	0.8
Taos	38.1	39.73	4.56[1]	26.08	27.72	8.33[1]	4 932	7 296.7	10.16[1]
Valencia	11.24	11.18	−0.1	20.58	23.09	10.69[1]	7 189.2	13 143	8.75[1]
Average	**20.17**	**22.08**	**6.10**[1]	**28.78**	**32.00**	**6.74**[1]	**20 647.9**	**18 767.6**	**−2.53**[1]

[1] Model significant at $P \leq 0.05$.

Auken, 2000; Polley et al., 2013). Higher CO_2 levels give a growth advantage to the C3 shrubs in a general sense with some exceptions (Van Auken, 2000). Actual research supporting this hypothesis has been lacking, but recently a Colorado study on native rangeland has confirmed its validity (Morgan et al., 2007). Over a 5-yr period aboveground biomass of a common shrub was increased severalfold, whereas C4 grasses were little impacted on plots with artificially elevated CO_2 compared with controls. Therefore it appears that the higher CO_2 levels driving climate change may have been an important factor favoring woody plant increases on New Mexico's rangelands.

Other Factors Influencing Grazing Level During the Study Period

On a short-term basis, droughts appeared to be the biggest causes of grazing level declines in New Mexico during our study period (see Fig. 7). However, the exception was the 1920s, when grazing levels dropped precipitously even though precipitation was 99% of the long-term average (see Fig. 7). This is probably explained by large-scale plowing of rangeland made possible by the development of tractors and associated mechanization in the early 1920s (Holechek, 2009). Tractors allowed farming of lands not easily tilled with draft animals and increased speed of tillage. During the 1920s, vast areas of rangelands unsuited for sustained cultivation were plowed in New Mexico and other Great Plains states (Gray, 1968; Holechek et al., 2003). This led to the "Dust Bowl" of the 1930s. Rapid expansion in the supply of farm commodities caused real farm income to drop 75% between 1919 and 1932 and was a major contributor to the Depression in 1932 (Holechek et al., 2003). The upward counter-trend in grazing levels in the late 1920s and early 1930s may be explained by conversion of some farmland back to rangeland as farmers went broke and their lands were absorbed by ranching operations. However, as the 1930s drought progressed and intensified, some ranchers were undoubtedly forced to liquidate part or all of their herds (see 1934, Fig. 7).

In the early 1940s the grazing level increase is explained by favorable precipitation and higher livestock prices associated with World War II (Gray, 1968). However, onset of drought in 1945 caused a drop in grazing levels. This was reversed by improved precipitation in the late 1940s and increased cattle prices in the Korean War period (1950 − 1952) (Gray, 1968). A sharp drop in grazing level occurred in 1956 due to severe drought. After 1957, the grazing level began increasing due to the 1950s drought ending and improved cattle prices (Gray, 1968). From 1963 until 1987, the grazing level was in a general downtrend even though precipitation was favorable and there were no severe droughts. We believe a combination of factors explain this downtrend. They relate to reduced forage from woody plant increase; increased regulation of livestock grazing on public lands within NM; managerial changes toward lower stocking rates to reduce risk, improve livestock productivity, and enhance rangeland condition; increased ranching costs due to rising oil prices in the 1970s; and bankruptcy of several ranches due to the high interest rates implemented by the US Federal Reserve Bank in the early 1980s to control inflation. We refer the readers to Holechek et al. (2011) for a more detailed discussion of these factors.

Grazing levels increased from 1988 through 1994, probably because of increasing cattle prices and above-average precipitation (1989 was the only yr of below-average precipitation). Declining precipitation, depressed cattle prices, and changes in government programs explain the drop in grazing level in the period from 1995 to 2003. The phasing out of drought emergency feed subsidy beginning in 1996 may in part explain the late 1990s decline. The emergency feed program compensated ranchers for about 50% of the cost of additional feed needed in drought years (Holechek and Hess Jr, 1995). The program was criticized for encouraging overgrazing and exacerbating rancher financial losses in drought years (Boykin et al., 1962; Holechek and Hess Jr, 1995; Holechek, 1996; Ward, 1998; Thurow and Taylor, 1999). Some ranchers routinely received compensation from the program even in wet years. It was replaced with an insurance program that monetarily compensates ranchers for forage lost in drought years.

Three other factors that account in part for some of the reduction in livestock grazing levels since 1980 include the assignment of more grazing capacity to wildlife on both private and public rangelands, changes in the nature of private land ownership, and selection of lower grazing intensity levels. On public lands demand for more wildlife, especially elk, has caused government agencies to reallocate grazing capacity away from livestock. On private lands, big game animals have become of major importance as a source of income in New Mexico, as in Texas (Knight, 1989; Wilcox et al., 2012).

In terms of the nature of private land ownership, the conversion of rangeland to uses other than livestock production as discussed by Wilcox et al. (2012) in Texas has been occurring in New Mexico but at a low level. The eastern half of New Mexico is dominated by private land away from urban centers and is used primarily for range livestock production. Western New Mexico is heavily dominated by federal and tribal lands managed for multiple uses that include range livestock

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production. Rangeland conversion to other uses has occurred primarily in the Albuquerque and Santa Fe areas of northcentral New Mexico and the Silver City area of southwestern New Mexico.

As reported by Wilcox et al. (2012) in Texas, ranchers in New Mexico have been shifting to lower grazing intensity levels for a variety of reasons. In New Mexico, these include compliance with grazing plans on public lands, desire for range condition improvement, reduction of drought risk, reduction in supplemental feed costs, reduction in replacement animal costs, and enhancement of wildlife habitat. Studies in New Mexico have shown conservative stocking involving about 35% use of forage to be advantageous over higher levels in terms of profitability, risk management, and range forage productivity (Holechek, 1992; Winder et al., 2000; Thomas et al., 2015). A 3-yr study across 41 grazing allotments in southern New Mexico found actual grazing use to be 34% (Navarro et al., 2002), confirming the widespread application of conservative stocking.

Implications

Since the 1970s, rangeland livestock levels and offtake as indicated by calf numbers have been in a downward trend in New Mexico. Precipitation was actually higher in the post-1970s compared with the pre-1970s. However, a definite warming trend has occurred in New Mexico since the mid 1970s with increasing frequent summer heat waves after 2000. Before 2000, only 2 yr (1934 and 1954) had air temperatures higher than 13.0°C compared with 4 yr (2003, 2012, 2016, and 2017) afterwards. Our review of research on global warming impacts on cereal crops indicates rangeland forage productivity is now being impacted by climate change. Ongoing long-term rangeland monitoring studies in New Mexico show sharp forage yield declines in years with near-average or above-average precipitation but summer heat waves. Information is lacking on how these heat waves are affecting livestock productivity. Downward trends in livestock production can also be attributed in part to woody plant increase (Fig. 8), which we believe has been accentuated by increasing atmospheric CO_2 levels (see Morgan et al., 2007). Dealing with direct and indirect impacts of climate change is becoming the major challenge for New Mexico range livestock producers and those in other parts of the world (Joyce et al., 2013; Polley et al., 2013).

The projected impacts of climate change on different North American rangeland types are discussed in detail by Polley et al. (2013). A comprehensive assessment of mitigation and adaptation strategies in response to climate change for rangeland livestock producers is provided by Joyce et al. (2013). We refer readers to these sources for specific management strategies for different range types, but we will make a few comments relevant to New Mexico.

We believe that the key to success for most arid and semiarid rangeland livestock producers under future global warming conditions will be containment of risk rather than maximization of production. Livestock prices will probably be quite favorable due to rising human populations confronting diminished production of most food crops, especially grains, as yields are increasingly depressed by heat waves and droughts. Under this scenario, grain will be mostly fed to people rather than livestock in order to avoid large-scale human starvation. Livestock production from ruminant animals will again be based around rangeland forage and crop residues that cannot be used directly as human food sources. The problems for livestock producers on arid and semiarid rangelands such as in New Mexico will likely be more erratic annual forage production due to droughts, frequent heat waves, and rising costs for supplemental feed inputs (Joyce et al., 2013; Gherardi and Sala, 2015; Havstad et al., 2016; McIntosh et al., 2019).

We believe a low-input approach to ranching as discussed by Holechek et al. (2011), Holechek (2013), and Thomas et al. (2015) will be effective for ranchers in arid and semiarid areas in terms of risk management. Although we consider climatic risk to be the greatest, other ranching risks that should not be overlooked include biological, financial, and political as defined by Holechek et al. (2011). It is important to recognize these risks intertwine as drought periods are typically coupled to falling local livestock prices due to herd liquidation (Holechek, 1996; Holechek, 2013). After a drought ends, the biological risk of disease infecting herds is increased due to ranchers purchasing livestock from outside sources for restocking. Ranchers must often pay inflated prices for inferior animals when restocking after drought (Thomas et al., 2015).

Appropriate stocking is essential for profitable and sustainable range livestock production (Holechek et al., 2011). It is the key element in avoiding devastating financial losses and damage to rangelands in drought periods. Reliable stocking rate procedures have been developed and evaluated by Holechek (1988), Holechek and Pieper (1992), Galt et al. (2000), and Thomas et al. (2015). The primary decision in setting the stocking rate is selection of the harvest coefficient (proportion of forage assigned to consumption by grazing animals). Guidelines on

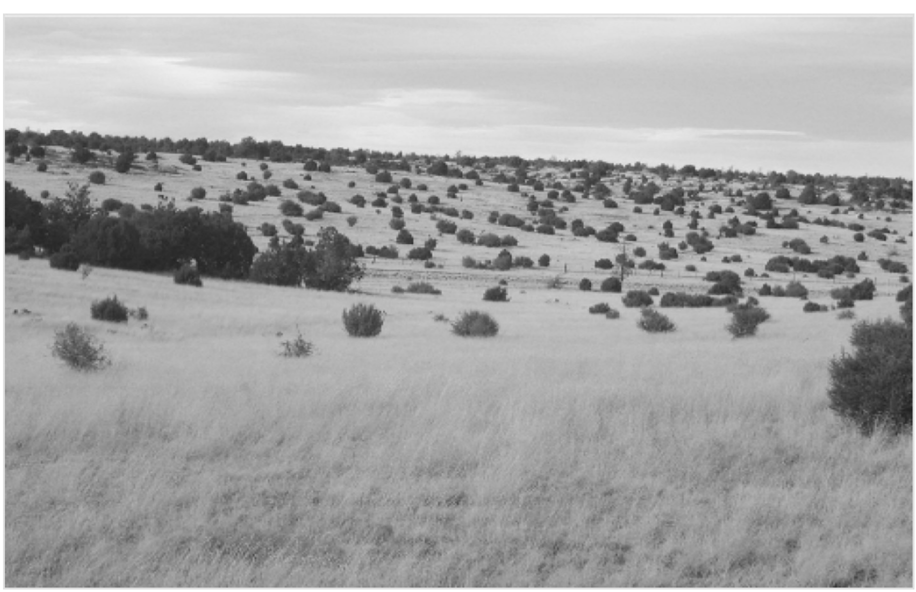

Figure 8. Pinyon juniper invasion into late seral grassland in Catron County, southwestern New Mexico. Prescribed burning is necessary to suppress trees and enhance forage production. (Photo by Jerry Holechek.)

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harvest coefficients for different types of rangeland are provided by Holechek et al. (2011). In general, a harvest coefficient of 35% has been recommended for arid and semiarid rangelands. It typically gives a 30 − 40% level of forage use, commonly referred to as conservative grazing, that optimizes forage production, livestock production, and financial returns (Holechek et al., 2011; Thomas et al., 2015). Light grazing involving a 25% harvest coefficient is a practical approach for cow-calf operators to minimize herd liquidation risk and maximize the rate of range recovery after drought (Thomas et al., 2015). Under conditions of worsening global warming, light grazing as discussed by Holechek (2013) and Thomas et al. (2015) will probably be the most effective stocking approach. Various rangeland researchers have recommended a 25% harvest coefficient be used when forage is allocated to livestock in stocking rate decisions (Lacey et al., 1994; Johnston et al., 1996; White and McGinty, 1997; Galt et al., 2000; Smart et al., 2010).

Livestock that can tolerate high air temperatures, lower feed quality, and higher disease levels will be essential for financial viability (Joyce et al., 2013). Selection for breeds or biotypes that readily use browse and have low water requirements will be essential. Sheep and goats will probably become financially more effective than cattle on most arid and semiarid rangelands because they can better handle air temperature extremes, require less water, better use rugged terrain, better use areas away from water, and make more use of browse (Heady and Child, 1994; Holechek et al., 2011). However, as global warming intensifies, replacing domestic livestock with wild animals (e.g., native and exotic deer, pronghorn, elk, oryx, sheep, African antelopes, and bison) that have the characteristics previously mentioned, are predator resistant, and require virtually no inputs will probably become the only financially viable way of range meat production on many rangelands. Wildlife ranching systems are already in place over large portions of Texas and can be complementary with conventional livestock production (Heady and Child, 1994; Holechek et al., 2011; Wilcox et al., 2012; Holechek and Valdez, 2018). Although sport hunting is the current motivation for wildlife ranching, we believe prices for all types of meat will rapidly ascend due to global human population increase and adverse impacts of global warming on crop production. These forces will likely necessitate nearly all ruminant meat come from rangelands. Meat from game animals is high in nutritional quality and commands a premium in Europe and Africa (Holechek and Valdez, 2018).

In this article, we have put our findings on trends in rangeland livestock production in a climate change context. We believe the fate of rangelands and rangeland livestock production in New Mexico is a good indicator of what is happening in several other parts of the world. This is because of its diversity of vegetation types and geographical position.

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