



Long-Term Declining Trends in Chihuahuan Desert Forage Production in Relation to Precipitation and Ambient Temperature[☆]



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ARTICLE INFO

Article history:

Received 1 December 2018

Received in revised form 9 May 2019

Accepted 10 June 2019

Key Words:

climate change
forage
grazing capacity
NDVI
phenometrics

ABSTRACT

Rising temperatures and more frequent droughts are posing new challenges to range livestock producers in the southwestern United States and many other parts of the world. We analyzed a 52-yr time series (1967–2018) of precipitation, ambient temperature, and perennial grass production (PGP), as well as 14 yr (2001–2014) of Moderate Resolution Imaging Spectrometer (MODIS)-derived vegetation phenometrics at a site in the Chihuahuan Desert of New Mexico. PGP was positively associated with December through September precipitation ($r = 0.69$; $P < 0.01$) but negatively associated with spring and summer (May–September) maximum average ambient temperature ($r = -0.47$; $P < 0.01$). PGP decreased by 43% in the second (1993–2018) compared with the first half (1967–1992) of our study (165 vs. 94 kg dry matter \bullet ha⁻¹; $P < 0.01$). Precipitation was lower and more erratic in the second half of the time series, decreasing by 18.6% (265.2 ± 15.0 vs. 215.8 ± 15.8 mm; $P = 0.01$). Conversely, mean maximum and mean ambient temperatures were higher during the 1993–2018 period (max T: 24.5 ± 0.1 vs. $25.3 \pm 0.1^\circ\text{C}$; $P < 0.01$; mean T: 14.4 ± 0.1 vs. $15.3 \pm 0.2^\circ\text{C}$; $P < 0.01$). MODIS-derived Normalized Difference Vegetation Index (NDVI) analysis showed that growing seasons began and ended later and became shorter ($P < 0.05$) over the 14 yr analyzed. During this period, increasing maximum spring and summer (May–September) ambient temperatures were associated with decreasing growing season NDVI values ($P < 0.01$). Over the 52-yr study period, Chihuahuan Desert rangelands at our research site lost 43% of grazing capacity based on PGP. Nine drought yr occurred in the second half of our study compared with 2 yr in the first half. Our research supports predictions by climate scientists that higher temperatures, more frequent droughts, and lower, as well as more erratic, precipitation will adversely impact grazing capacity of rangelands in the southwestern United States.

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Introduction

Throughout the world, climate change is jeopardizing rancher and pastoralist livelihoods and chances for achieving their goals, which typically include sustainable output of animal products and conservation of soil and vegetation resources (Havstad et al., 2007; Havstad et al., 2018). Various models predict major changes in

climate for different grazing regions of the United States during this century (Karl and Trenberth, 2003; Polley et al., 2013; Greene and Seager, 2016; USGCRP, 2017, 2018). Both globally and nationally, the impacts of climate change are better understood for crops grown under agronomic conditions than for rangeland-based livestock production systems (Bourne, 2015; Briske et al., 2015; World Resources Institute, 2018). Rangeland livestock production in semi-arid and arid regions, such as the southwestern United States, will likely be more adversely impacted by climate change than areas with moderate or high levels of precipitation. In the southwestern United States, it is predicted that increased warming and more frequent droughts will result in decreased soil water availability; altered growing seasons; suppressed recruitment, growth and nutritive value of forages; and shifts in plant species composition (Polley et al., 2013; Briske et al., 2015; Havstad et al., 2018).

Site-specific information regarding the impacts of changing climate regimes on rangeland livestock grazing capacity is both

[☆] This research was supported by the New Mexico Agricultural Experiment Station (Project 072944). It was funded with a grant from the US Dept of Agriculture National (USDA) Institute of Food and Agriculture, Hatch Funds to J. L. Holechek and A. F. Cibils (Grant # 1019148). Partial funding was provided by the USDA Agricultural Research Service Jornada Experimental Range and the Long-Term Agroecosystem Research (LTAR) network.

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lacking and needed (Briske et al., 2015). Sound procedures have been developed for determination of carrying capacity and setting stocking rates on rangelands, but they depend on accurate estimates of forage production (Holechek et al., 2011). Although determination of forage production is typically time consuming and expensive, reasonably reliable estimates of forage production for various rangeland types in the western United States have been obtained from regression equations based on annual precipitation amount and timing (Khumalo and Holechek, 2005; Holechek et al., 2011). Information is now needed on the reliability of these models because, in many areas, global warming may have already significantly altered the precipitation and temperature regimes that drive forage production.

At the beginning of the 20th century, perennial grasslands dominated vast landscapes in the northern Chihuahuan Desert of New Mexico (Lohmiller, 1963; Buffington and Herbel, 1965; Gibbens et al., 2005). However, by the end of the 20th century these areas were reduced to < 7% of the total area (Gibbens et al., 2005). Overgrazing (followed by nutrient depletion) is considered the primary factor involved in the replacement of grassland with shrubland in the Chihuahuan Desert (Schlesinger et al., 1990; Bestelmeyer et al., 2006b). However, several other factors including altered fire regimes, increased ambient CO₂, increased rodent populations, and the severe drought of the 1950s are also implicated as principal drivers of shrub encroachment (Lohmiller, 1963; Buffington and Herbel, 1965; Gibbens et al., 1992, 2005; Bestelmeyer et al., 2006b; Kidron and Gutschick, 2013, 2017).

Various studies in the Chihuahuan Desert have shown that upland perennial grasses (the primary forage component for live-stock, especially cattle) are better maintained by light to conservative grazing intensities (20–40% use) than under heavier grazing intensities or no grazing use (Paulsen Jr. and Ares, 1962; Valentine, 1970; Holechek et al., 2003; Thomas et al., 2015). Following the 1950s drought until 1994, perennial grass cover and productivity on lightly to conservatively stocked pastures on the Chihuahuan Desert Rangeland Research Center (CDRRC) in south central New Mexico were in a general upward trend (Valentine, 1970; Beck et al., 2007). However, since 1994, perennial grass production (PGP) has been on a downward trend despite light to conservative grazing intensities having been applied in years of near normal to above normal precipitation and pastures having been completely destocked in severe drought years (Beck et al., 2007; Sawalhah, 2014; Thomas et al., 2015). On the basis of recent research (Kidron and Gutschick, 2017) evaluating climatic effects on long-term rangeland vegetation trends at two different locations in New Mexico's Chihuahuan Desert, we believe changing temperature and precipitation characteristics could provide an explanation for the downward trend in PGP on the CDRRC since 1994.

A long-term database has been collected for pasture 1 (P1) on the CDRRC since the late 1960s (Beck et al., 2007; Sawalhah, 2014; Thomas et al., 2015), which has allowed us to examine trends and interrelationships in PGP, vegetation phenometrics, and climate. Our overall goal in this paper is to assess the magnitude of climatic change, focusing on temperature and precipitation, on P1 on the CDRRC over the past 52 yr (1967–2018) and to infer its possible impact on rangeland grazing capacity in terms of PGP. In most years, PGP accounts for > 85% of the forage grazable by cattle on the CDRRC (Molinar, 1999; Beck et al., 2007; Sawalhah, 2014). Stocking rate procedures that use only PGP as grazable forage have proven reliable in achieving grazing use targets based on long-term studies (Beck et al., 2007; Thomas et al., 2015). We consider P1 on the CDRRC to be representative of large areas of upland northern Chihuahuan Desert rangeland. It is similar in species composition, terrain, and climate to various southern New Mexico landscapes described by Navarro et al. (2002) in a rangeland condition and trend study. Our specific objectives were to determine if 1)

differences occurred in precipitation (mm), drought frequency, daily temperatures (°C), and PGP (kg • ha⁻¹) between two periods (1967–1992 vs. 1993–2018); 2) PGP could still be predicted using regression functions developed by Khumalo and Holechek (2005); 3) vegetation green-up dynamics based on phenometrics changed over the 2001–2014 period; and 4) climate and vegetation phenometrics trends were related. We used two independent approaches to examine the relationships between desert vegetation and climate. First, we analyzed detailed records of perennial grass production, monthly precipitation, and daily temperatures collected over a 52-yr period. Second, we analyzed phenometric parameters from 14 yr of biweekly MODIS-derived Normalized Difference Vegetation Index (NDVI) data collected on our research site.

Materials And Methods

Study Area Description

Our 1 267-ha study pasture is located on New Mexico State University's CDRRC (latitude 32°32'30"N, longitude 106°52'3"W) ≈ 37 km north of Las Cruces, in Doña Ana County, New Mexico. Historical and physical descriptions of our study area are provided by Holechek et al. (1994), Molinar (1999), Khumalo and Holechek (2005), Beck et al. (2007), Sawalhah (2014), and Thomas et al. (2015). Specifically, our study area is 1) the “yearlong pasture” in the long-term study comparing yearlong and seasonal suitability grazing reported by Beck et al. (2007) and 2) “pasture 1” (light graze treatment) in the long-term study comparing light and conservative grazing reported by Thomas et al. (2015; Fig. 1b).

The CDRRC is located at the northern end of the Chihuahuan Desert and southern portion of the Jornada del Muerto Plains (see Fig. 1a). It lies between the San Andres Mountains to the east and Rio Grande Valley to the west. Study site elevation varies from 1330 to 1340 m, and ecological sites include shallow sandy (40%), sandy (40%), and deep sandy (20%; Molinar, 1999; NRCS, 2017). Soils of this area are loamy fine sand, sandy clay loam mixed calcareous coarse-loamy alluvium of the Berino-Bucklebar and Wink-Harrisburg associations with a depth of 50–100 cm to the restrictive petrocalcic horizon (Molinar, 1999; NRCS, 2017). Fines percentages per soil type include 9–18%, 18–51%, 17–20%, and 16% silt for Berino, Bucklebar, Wink, and Harrisburg, respectively, and 5–35%, 10–35%, 8–18%, and 3–18% clay for Berino, Bucklebar, Wink, and Harrisburg, respectively (NRCS, 2017). The reader is referred to Bestelmeyer et al. (2006a) for a detailed description and review of ecological research from the Jornada Basin, where our study pasture is located.

Vegetation

Primary grass species in the study area include black grama (*Bouteloua eriopoda* Torr.), dropseeds (*Sporobolus* spp.), threeawns (*Aristida* sp.), bush muhly (*Muhlenbergia porteri* Kunth.), fluffgrass (*Erioneuron pulchellum* Tateoka), tobosa (*Hilaria mutica* Buckley), sixweeks' grama (*Bouteloua barbata* Lag.), vine mesquite (*Hopia obtusa* Kunth.), sandbur (*Cenchrus spinifex* Cav.), and burrograss (*Scleropogon brevifolius* Phil.; see Fig 1e). Depending on year, black grama, the primary upland “decreaser” perennial grass in the Chihuahuan Desert, has comprised about 40–65% of the perennial grass composition (by weight) of our study pasture (Molinar, 1999; Khumalo, 2006; Sawalhah, 2014). Across years, black grama, dropseeds, threeawns, and other grasses accounted for 55%, 22%, 14%, and 9% of perennial grass production, respectively (Beck et al., 2007; Sawalhah, 2014). Combined, black grama, dropseeds and threeawns have comprised > 90% of perennial grass composition by weight in most years (Molinar, 1999; Beck et al., 2007; Sawalhah,

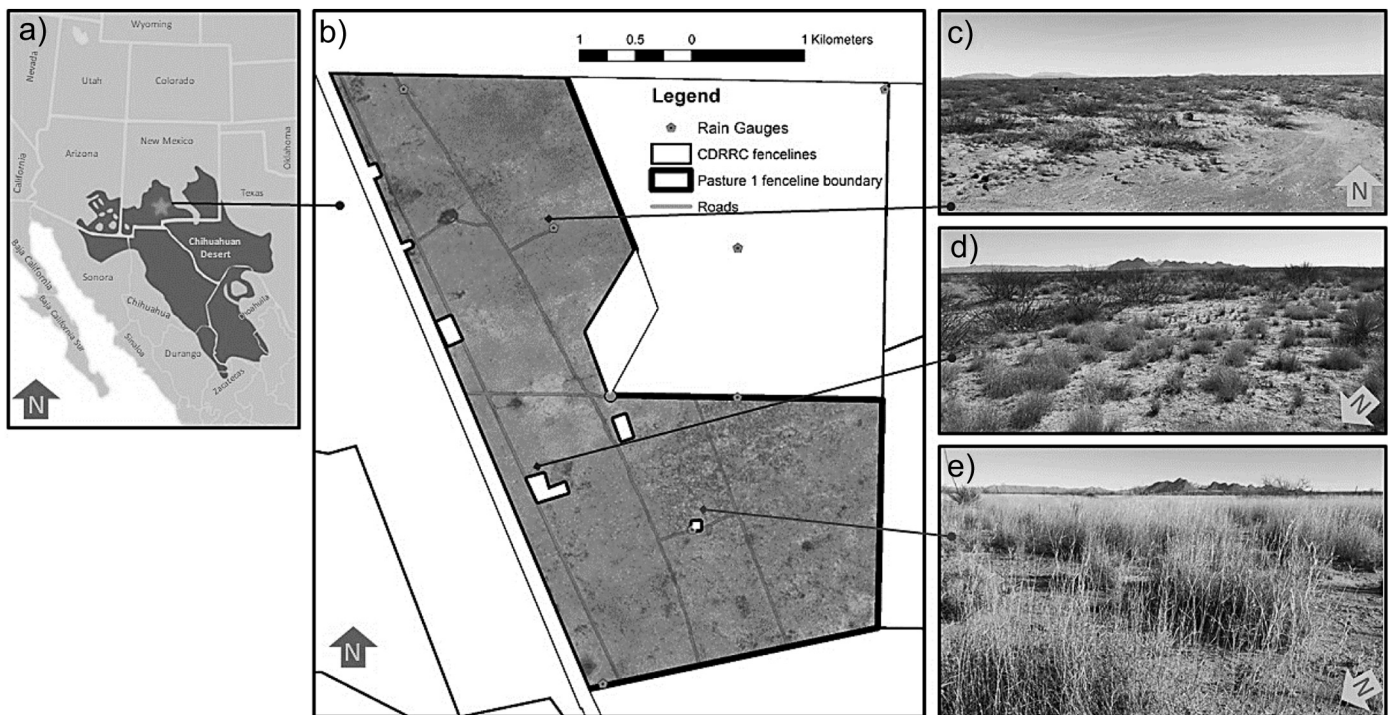


Figure 1. (a) Study site location within Chihuahuan Desert, (b) satellite map of Pasture 1, ecological sites in order from most (c) mesquite dominant to (d) a mesquite-black grama grassland to (e) a black grama dominant site within our study pasture at the Chihuahuan Desert Rangeland Research Center.

2014). Bush muhly is the fourth most important perennial grass on P1 and usually accounts for 5–8% of total PGP.

Primary shrub species include honey mesquite, broom snake-weed (*Gutierrezia sarothrae* [Pursh] Britton & Rusby), and creosotebush (*Larrea tridentata* [DC.] Coville; Molinar, 1999; see Fig. 1c). Secondary shrubs include yucca (*Yucca elata* av.), four-wing saltbush (*Atriplex canescens* [Pursh] Nutt.), and desert zinnia (*Zinnia acerosa* [DC.] Kuntze). Common forbs include leatherweed croton (*Croton pottsii* Lam.), Gordon's blatterpod (*Physaria gordonii* [A.Gray] O'Kane & Al-Shehbaz), twin leaf senna (*Senna bahinioides* [A. Gray] Irwin & Barneby), silverleaf nightshade (*Solanum elaeagnifolium* Cav.), devil's claw (*Proboscidea parviflora* [Woot.] Woot. & Standl.), Desert Holly (*Acourtia nana* [A. Gray] Reveal & R.M. King), Coyote melon (*Cucurbita palmata* S. Wats.), and onehead brittlebush (*Encelia scaposa* A. Gray). Cactus species also include prickly pear cactus (*Opuntia* sp. Mill.) and cane cholla (*Cylindropuntia imbricata* [Haw.] DC.).

Periodically, beginning in 1995, we evaluated vegetation basal cover on 10 key areas on our study pasture (Sawalhah, 2014). Total vegetation basal cover has varied from 3.6% in 1995 to 11% in 2005. In 1995, grasses, forbs, and shrubs comprised 33%, 39%, and 28% of total perennial plant basal cover (1.8%) compared with 25%, 22%, and 53% in 2005 (total perennial plant cover = 5.5%). Honey mesquite canopy cover and density were further evaluated on the 10 key areas using belt transects (Molinar, 1999; Sawalhah, 2014). Both canopy cover (5% in 1995, 9% in 2018) and density of honey mesquite have increased in the 1995–2018 period (Sawalhah, 2014, unpublished 2018 data).

Climate

The climate at CDRRC is arid with an average total of 200 frost-free d. Temperature data collected from 1936 to 2018 at the headquarters of the neighboring Jornada Experimental Range (JER; latitude 32°37'01"N, longitude 106°44'30"W) indicate an annual mean of 14.7°C and an annual mean maximum temperature of

24.9°C. High temperatures occur in the summer (June, July, August) with the greatest monthly mean in July at 29.8°C. Spring (March, April, May); summer; fall (September, October, November); and winter (December, January, February) temperatures average 14.2°C, 24.9°C, 15.0°C, and 4.7°C, respectively. Prevailing spring winds are associated with vegetation water stress and cause aeolian topsoil movement and erosion (Pieper and Herbel, 1982; Ravi et al., 2010).

The Chihuahuan Desert has a bimodal pattern of annual precipitation with high-intensity to low-frequency convective storms occurring in mid–late summer (July–September) and gentle precipitation events occurring in winter (December–February; Khumalo and Holechek, 2005). Precipitation data collected from 1936 to 2018 at our study site indicate an annual mean of 259.2 mm, with 18.2% of the annual rainfall occurring in summer, 22.3% occurring in winter, 22.3% occurring in spring, and 37.2% occurring in autumn.

Vegetation and Management History

Historical descriptions for P1 are provided by Valentine (1970), Holechek et al. (1994), Molinar (1999), Khumalo and Holechek (2005), and Beck et al. (2007). The study area (P1) has a generally flat to rolling terrain that was predominantly a black grama grassland when the CDRRC was established in 1927. Since then, P1 has been managed using light to conservative continuous year-long grazing by cattle. During the 1930s and 1940s, forage production averaged near 360 kg • ha⁻¹, the cattle stocking rate averaged 40 ha per animal unit (AU), and forage use averaged about 35%. Black grama cover reportedly dropped because of a 1953–1956 drought, and livestock were temporarily removed from the study area (Khumalo and Holechek, 2005). Grazing has been closely controlled since 1967 when the stocking rate was reduced to 67 ha • AU⁻¹ and a 20–30% forage-use level was targeted (Beck, 1978; Holechek, 1991; Holechek et al., 1994; Khumalo and Holechek, 2005; Beck et al., 2007). In the 1967–2018 period, estimated forage use has averaged 26% ranging from 8% to 43% depending on year. Detailed

descriptions of forage use measurement on P1 are provided by Beck et al. (2007) and Thomas et al. (2015). Forage use measurements were taken in late June of each year because it is the end of the forage cycle before new growth of perennial grasses, which usually occurs in July. Procedures (for measuring use) involved determination of percent use of forage by weight on four key areas in P1 that were considered representative of grazing intensity (Holechek and Galt, 2000; Beck et al., 2007). Stubble heights of black grama, dropseeds, and threeawns were also measured and used to make decisions regarding destocking in drought years using guidelines of Valentine (1970) and Holechek and Galt (2000).

Perennial Grass Production

Beginning in 1967 and continuing through 2002, 92 randomly located fixed transects, ≈ 67 m each in length, were sampled yearly in P1 (McNeely, 1983; Beck et al., 2007). Transects were oriented in an east–west direction and bounded on each end by a steel stake. PGP was measured annually at each transect at the end of each growing season by clipping five 0.3-m^2 plots every 12 m along the permanent transect to a 2-cm height using hand clipping shears (Khumalo and Holechek, 2005; Beck et al., 2007). Plots were shifted 1 m forward each year to avoid previously clipped areas. Vegetation was separated by species and current yr's growth in the field, then oven dried and weighed to determine annual $\text{kg DM} \cdot \text{ha}^{-1}$ (Khumalo and Holechek, 2005; Beck et al., 2007).

In 1995, a new system was developed to evaluate PGP. Ten key areas were identified and evenly spaced across the study area (Molinar, 1999). Autumn PGP and standing crop were determined using ten 0.5-m^2 quadrats at 6.1-m intervals along a 61-m line transect bounded at 0 m, 30.5 m, and 61 m by steel stakes (Molinar, 1999; Khumalo and Holechek, 2005). The perennial grass biomass results of this method were found to be comparable ($R^2 = 0.84$) with those of McNeely (1983) and Beck et al. (2007) for the 1995 through 2002 period when both sampling systems were implemented. Therefore, data from the new sampling system were used from 1995 forward in this study.

From 1969 to 1976, data from two rain gauges located in pasture 1 were used to determine monthly precipitation. From 1977 to 2017, two additional rain gauges were installed and the average of all four gauges (1: latitude $32^\circ 33' 23.41''\text{N}$, longitude $106^\circ 55' 20.10''\text{W}$; 2: latitude $32^\circ 34' 46.68''\text{N}$, longitude $106^\circ 54' 36.11''\text{W}$; 3: latitude $32^\circ 35' 34.49''\text{N}$, longitude $106^\circ 55' 39.72''\text{W}$; 4: latitude $32^\circ 36' 13.65''\text{N}$, longitude $106^\circ 56' 31.66''\text{W}$) were used to determine monthly precipitation for that period. Temperature data were recorded at the neighboring JER headquarters ≈ 17.3 km NE from our study site. Daily maximum and minimum temperatures were recorded beginning in 1914 through 2018. Annual CO_2 dry air mole fractions ($\text{micromole} \cdot \text{mol}^{-1}$; expressed as ppm) were obtained from the National Oceanic and Atmospheric Administration (NOAA) and Earth System Research Laboratory (ESRL)—Global Monitoring Division in Moana Loa, Hawaii (latitude $19^\circ 32' 11''\text{N}$, longitude $155^\circ 34' 35''\text{W}$). Recording of annual CO_2 dry air mole fractions was initiated in 1959 and continued through 2018. Monthly and seasonal average precipitation, mean ambient temperature, and mean ambient maximum temperature data by year were used as climatological explanatory variables of PGP (Fig. 2).

Vegetation Phenology

To assess the influence of climate and weather on vegetation phenology, we acquired MODIS 16-d composite 250-m time-series NDVI (MOD13Q1 data product) for January 2001 through December 2014. We summarized NDVI to the research-site level by averaging the NDVI of all 250-m pixels in the pasture with the result of one value per 16-d period. We then calculated growing season metrics

for each yr (2001–2014) with TIMESAT (Jönsson and Eklundh, 2004; Browning et al., 2018), using the Savitzky-Golay filter and 0.15 as the seasonal amplitude threshold to accommodate years with high and low NDVI values. TIMESAT provided a smoothed function of NDVI for each of the 14 yr and specified the following metrics for the growing season curve per year: growing season start date, growing season end date, length of growing season, time of middle of season (the mean value of the times for which the left edge increased to the 80% level and the right edge decreased to the 80% level), peak value (maximum value of fitted data in that yr), amplitude (the difference between peak value and base level), left derivative (rate of increase at the beginning of the season), right derivative (rate of decrease at the end of the season), large season integral (integral of the function describing the season from the season start to the season end with no meaning when part of the fitted function is negative), small integral (integral of the difference between the function describing the season and base level from season start to season end), start value, end value, base-level value (average of the left and right minimum values). There was no detectable green-up in 2002, so phenometrics for this year were excluded from analyses reducing our NDVI time series to 13 yr.

Statistical Analyses

To evaluate the relationships between PGP (52 yr) or NDVI-derived phenometrics parameters (13 yr) and precipitation or ambient temperature, we used simple linear regression and correlation analyses via the PROC CORR and PROC REG procedures in SAS 9.4 (Neter and Wasserman, 1974; SAS Institute, Cary, NC, USA). We used PROC TTEST in SAS 9.4 (SAS Institute, Cary, NC) to compare precipitation, temperature, forage production, and atmospheric CO_2 concentrations in the first and second halves of our study period. We also conducted multiple regression analyses using the PROC REG and PROC GLM procedures in SAS 9.4 (SAS Institute) to determine the feasibility of predicting perennial grass production using either weather variables (52 yr) or phenometrics variables (13 yr) as predictors. We used Mallows' C_p as our variable selection method (Mallows, 1973) and conducted diagnostic analyses to test for violations of linearity assumptions. We also calculated variance inflation factor coefficients to screen for possible autocorrelation among predictors. All statistical tests were deemed significant at $P \leq 0.05$.

Results and Discussion

Precipitation, ambient temperature, atmospheric CO_2 , and PGP all differed ($P < 0.05$) between period 1 (1967–1992) and period 2 (1993–2018; Table 1). PGP average was 43% greater in period 1 than period 2. Precipitation average was 18.6% greater and showed slightly lower yr-to-yr variation in period 1 versus period 2 (see Table 1). These differences may have driven the decline in PGP. Cooler mean annual and mean maximum ambient temperatures occurred in period 1 versus period 2 and may have also contributed to the forage production difference between the two periods (see Table 1). On the basis of comparative research by Kidron and Gutschick (2017) at two separate sites in the Chihuahuan Desert of New Mexico, increased temperatures can adversely impact perennial grasses by reducing soil surface wetness through increasing evaporation.

The 0.8°C increase in mean temperature in the second period of our study was accompanied by an 11.2% increase in atmospheric CO_2 (see Table 1). The temperature increase at our study location is consistent with WMO (2018) data showing that significant global warming has occurred in response to increased GHG emissions over the past 25 yr. Our temperature data from the JER support the concern by the International Panel on Climate Change (IPCC, 2018)

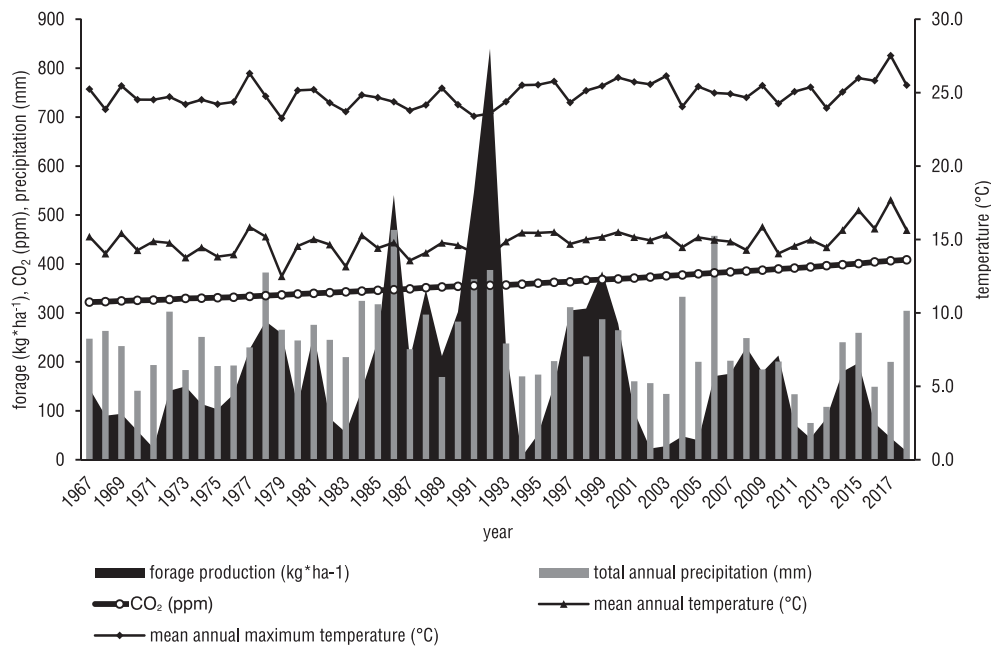


Figure 2. Long-term graphical trends of: forage production ($\text{kg}\cdot\text{ha}^{-1}$), annual total precipitation (mm), mean annual ambient temperature ($^{\circ}\text{C}$), mean annual ambient maximum temperature ($^{\circ}\text{C}$), and annual ambient CO_2 (ppm) from 1967 – 2018.

that another 0.5°C increase will likely occur within 20 yr if world leaders do not act soon to check GHG emissions. By 2040 this will put the global temperature increase at the 1.5°C threshold, above which there is high risk of climatic catastrophe (USGCRP, 2017, 2018; IPCC, 2018; Steffen et al., 2018).

Average annual precipitation in our study area during the 52-yr period was 3% above (239.9 mm) the long-term (88-yr) average for the CDRRC (234 mm; Thomas et al., 2015). In the first and second halves of the study, precipitation was 14% above (257.4 mm) and 10% below (210.2 mm) the long-term average, respectively. Drought as defined by the Society for Range Management (1989) is prolonged dry weather when precipitation is generally $< 75\%$ of the average annual amount. On this basis, only 2 drought yr (1970, 1989) occurred in the first half of our study compared with nine (1994, 1995, 2001, 2002, 2003, 2011, 2012, 2013, 2016) in the second half (Table S1; available online at <https://doi.org/10.1016/j.rama.2019.06.002>). Three distinct periods of extended drought (≥ 2 consecutive drought yr) occurred in the second half of our study while none occurred in the first half.

When forage production drops below $100 \text{ kg}\cdot\text{ha}^{-1}$, livestock grazing usually becomes financially unsound (Stoddart and Smith, 1943; Holechek, 1996). This is because of high fixed costs per animal unit and low livestock productivity due to high energy expenditure in travel to meet nutritional needs (Stoddart and

Smith, 1943; Holechek, 1996). PGP dropped below the $100 \text{ kg}\cdot\text{ha}^{-1}$ level in 6 yr of the first study period and 13 yr of the second period (see Table S1). Consecutive yr of PGP below the $100 \text{ kg}\cdot\text{ha}^{-1}$ level occurred from 1968 to 1971, 1982 to 1983, 1994 to 1995, 2001 to 2005, 2011 to 2013, and 2016 to 2018.

In 2017 and 2018, PGP was below $50 \text{ kg}\cdot\text{ha}^{-1}$ despite precipitation levels being above and near average (see Table S1). We attribute this to above-average temperatures in 2017. An exceptionally severe heat wave occurred in 2017 lasting from mid-May into early August with daily temperature highs routinely above 40°C ($5\text{--}6^{\circ}\text{C}$ above normal; Freedman, 2017; Geiling, 2018; Smith, 2018). We believe the depressed PGP in 2004 is explained by unusually hot, dry growing season conditions in the 2001–2003 period, which both weakened and killed a high percentage of perennial grass plants, especially dropseeds, based on our visual observations (see also Beck et al., 2007, who made similar observations). Typically, the metabolism of actively growing endemic plant species is disrupted when extreme temperature aberrations occur outside their range of adaptation (Hatfield and Prueger, 2015). As with grain crops (Asseng et al., 2011; Derying et al., 2014; Challinor et al., 2014), our research indicates that months with above-average temperatures during the growing season can depress yields of rangeland forage grasses, but this and the effects of heat waves need more detailed study.

Table 1
Student's *t*-test two-sample assuming equal variances of forage ($\text{kg}\cdot\text{ha}^{-1}$), annual total precipitation (mm), mean annual ambient temperature ($^{\circ}\text{C}$), mean annual ambient maximum temperature ($^{\circ}\text{C}$), and annual ambient CO_2 (ppm) between first (1967–1992) and last (1993–2018) halves of our study period.

Variable	1967–1992	1993–2018	<i>P</i>	Δ	% Δ
	Mean	Mean			
Annual forage production ($\text{kg}\cdot\text{ha}^{-1}$)	165.0 ^x	94.0 ^x	*	–71.0	–43.0
Annual total precipitation (mm)	265.2 \pm 15.0	215.8 \pm 15.8	*	–49.4	–18.6
Mean annual ambient temperature ($^{\circ}\text{C}$)	14.4 \pm 0.1	15.3 \pm 0.2	**	+0.8	+5.9
Mean annual ambient maximum temperature ($^{\circ}\text{C}$)	24.5 \pm 0.1	25.3 \pm 0.1	**	+0.8	+3.2
Annual ambient CO_2 (ppm)	338.5 \pm 2.1	381.3 \pm 3.1	**	+42.8	+11.2

^x variables without standard errors are variable medians; these variables were non-normally distributed and were log transformed to meet the assumptions of this model.

* Significant at $P < 0.05$.

** Significant at $P < 0.01$.

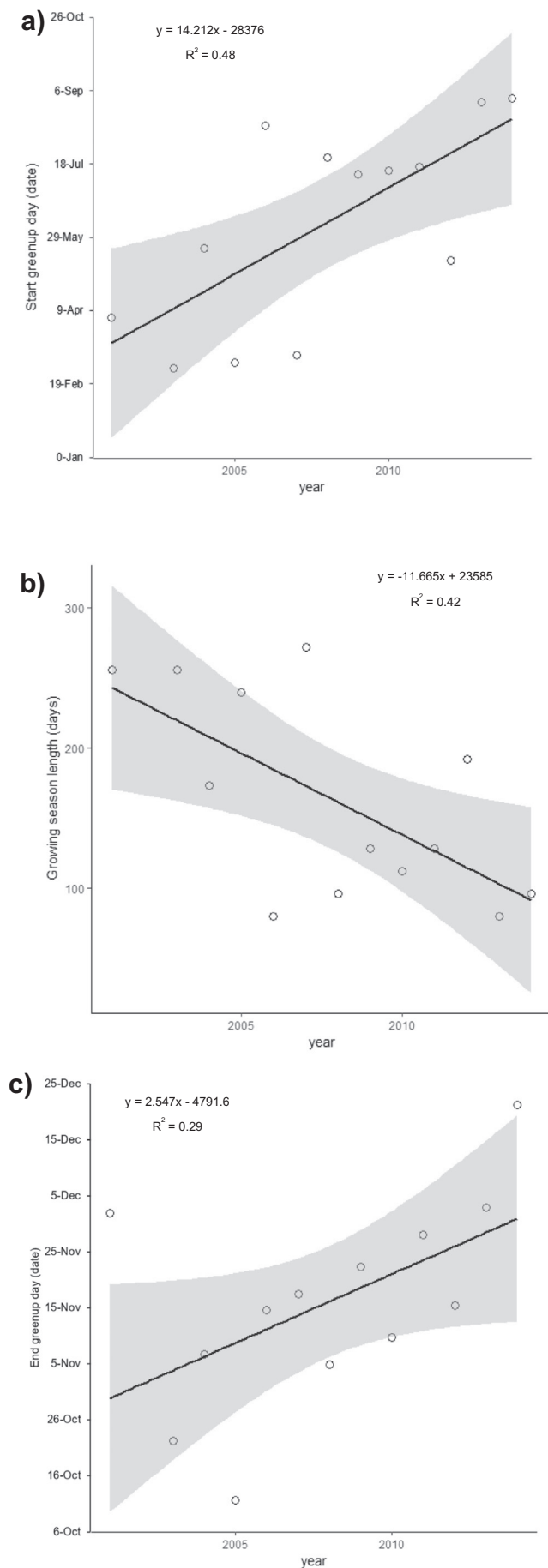
Growing season climatic conditions in the previous year play an important role in current-year perennial grass production (Cable and Martin, 1975; Khumalo and Holechek, 2005; Sala et al., 2012). Lags in perennial grass production can occur at time scales shorter than a year due to soil moisture deficiency (Beck et al., 2007; Sala et al., 2012). Time lags and legacies can play an important role in long-term perennial grass productivity in arid and semiarid rangelands (Beck et al., 2007; Sala et al., 2012). Beck et al. (2007), on the CDRRC, and Paulsen and Ares (1962), on the adjacent JER, both reported that timing and spacing of growing season rainfall events are important factors governing variation in perennial grass production among years. As an example, dropseed production on the CDRRC has been in a general downtrend since 1992, apparently explained in part to a legacy event described later (Beck et al., 2007). Temperature requirements for dropseeds to initiate growth are less exacting than for black grama, and they initiate vigorous growth if spring moisture is available (Beck et al., 2007). In 1992, April and May precipitation on CDRRC pastures (pasture 1 included) was about five times the normal average (Beck et al., 2007). After this period of exceptional rainfall in which a very high level of dropseed germination was observed, a hot, dry period lasting nearly 8 wk occurred in June and July. During this dry period, many of the established older dropseed plants showed major dieback and large-scale mortality occurred in small plants that germinated in April and May. Due to high seedling mortality and low seed production in 1992, followed by the onset of drought in late summer 1993, Beck et al. (2007) speculated there was little dropseed left in the soil to germinate, establish, and contribute to perennial grass production after the drought broke in 1996. We refer the reader to Sala et al. (2012) for more detailed discussion of precipitation and associated soil moisture legacies on annual net primary production on arid and semiarid lands.

Nine of the 10 yr with lowest PGP all occurred in the second half of our study (Table S2; available online at <https://doi.org/10.1016/j.rama.2019.06.002>). In contrast, 6 of the 10 yr with the highest PGP occurred in the first study period. Vegetation phenology analyses showed that between 2001 and 2014 (all within period 2 of our study), growing seasons became progressively shorter and green-up and brown-down tended to occur at increasingly later dates (Figs. 3a and c). This apparent shift in vegetation phenology, which agrees with climate model predictions of a delayed annual monsoon season in the southwestern United States (Cook and Seager, 2013), may have been associated with suppressed growth of perennial grasses, all of which exhibit the C₄ photosynthetic pathway. High occurrence of drought years in the second study period also support projections based on climatic models that predict drought frequency and severity in the southwestern United States will escalate due to global warming over the coming decades (Seager and Vecchi, 2010; Polley et al., 2013; Greene and Seager, 2016; USGCRP, 2017, 2018). However, Greene and Seager (2016) point out there is considerable uncertainty in these predictions due to natural climate variability and model structural limitations. The warming and drying from the climatic change process are projected to reduce PGP (hence grazing capacity) through lower soil water availability and increased heat stress (Polley et al., 2013). More wet years may occur as well as dry years, but increased summer temperatures and heat waves may nullify the positive effects of wet years on perennial grass production. We note that average annual temperatures in the past 6 yr (2013–2018) of our study were 1.2°C greater than the previous 6 yr (2007–2012; see Table S1). Although Peters et al. (2013) found no long-term trends in precipitation or temperature for a historical dataset from the JER (1925–2008), our recent 6-yr comparisons and first (1967–1992) and last (1993–2018) study period comparisons showed both a warming trend and a tendency for more variable precipitation in recent years. These data and those at the global level (IPCC, 2018;

WMO, 2018) indicate the climate warming trend may be accelerating. We note, also, that when the last 6 yr of our study were compared with the first 6 yr (1967–1972), the temperature increase was slightly greater (1.3°C).

The influence of abiotic factors, especially temperature, on New Mexican Chihuahuan Desert vegetation was studied in detail by comparing two equivalent sites (primary grass black grama) that had been degraded by past heavy grazing but allowed to recover over a period of 30 yr (Kidron and Gutschick, 2017). Soil and precipitation characteristics were similar, but temperature was lower on the Sevilleta National Wildlife Refuge (SEV) site, which was 200 km north of the JER site. The SEV site had a significant increase in perennial grass cover after livestock grazing was excluded in 1973, while no increase occurred on the JER, which had been lightly grazed since 1947. Summer temperatures were higher ($\approx 3^\circ\text{C}$), relative humidity was lower, rainstorm duration was shorter, and hourly wind speed was higher on the JER than the SEV. Time duration that the soil remained wet in the summer was apparently below that needed for successful perennial grass establishment on the JER (adjacent to the CDRRC). In conclusion, the authors pointed out that temperature increase appeared responsible for plant composition change, which may further lead to broad consequences for ecosystem hydrology, structure, and function. Sandy soils with a low silt/clay content characterized both areas; however, soil organic matter and nitrogen content are actually lower on the SEV than on the JER, which tends to refute the theory advanced by Schlesinger et al. (1990) that altered soil properties from past heavy grazing are a major impediment in perennial grass recovery on the JER (Kidron and Gutschick, 2017). With progression of global warming, the threshold soil moisture content for perennial grass establishment may increasingly not be met in semiarid ecosystems (Kidron and Gutschick, 2017).

Shrub encroachment is considered to be an important factor affecting long-term PGP on Chihuahuan Desert rangelands (Gibbens et al., 1992; Beck et al., 2007). Both increased winter temperatures, and higher atmospheric CO₂ levels associated with climate change theoretically benefit shrubs (Van Auker, 2000; Morgan et al., 2007). The primary woody plant on our study area is honey mesquite, which accounts for > 90% of the shrub cover when the half-shrub broom snakeweed is excluded (Molinar, 1999; Sawalshah, 2014). Mesquite canopy cover on our study area was 5% at study initiation (1995) and 9% in 2018 on the basis of long-term monitoring (Molinar, 1999; Sawalshah, 2014; unpublished 2018 data). Generally, honey mesquite canopy cover levels must reach 15–20% to significantly affect forage production (Scifres and Polk, 1974; McDaniel et al., 1982; Warren et al., 1996). Because honey mesquite canopy was well below the 15% level on our study area, we do not believe it was an important factor affecting long-term PGP. It is important to note, however, that increasing variability in annual precipitation has been shown to favor shrub growth and suppress PGP in the Chihuahuan Desert. A 6-yr manipulation experiment using rain-out shelters at a location not far from our research site reported that increasing yr-to-yr rainfall variability (keeping overall precipitation levels constant) promoted a 61% increase in shrub productivity and an 86% reduction in grass production (Gherardi and Sala, 2015). Interannual variation of precipitation at our site increased slightly in the second versus the first half of our study (see Table 1). This difference could have also contributed to the declining perennial grass production trend observed at our site. On the adjacent JER, Kidron and Gutschick (2013) found evidence of coexistence between shrubs and grasses and undercanopy grass that does not support the notion of high competition between these plant groups. They suggested that lower soil water availability during the summer rather than competition from shrubs may best explain the decline in perennial grass cover on the Jornada Basin over the past 100 yr.



PGP and a number of monthly or seasonal precipitation values were positively correlated (Table S3; available online at <https://doi.org/10.1016/j.rama.2019.06.002>). However, none of the correlations were at or above the 0.8 level we consider necessary for predictive potential. PGP was best correlated with December through September precipitation ($r = 0.69$, $P < 0.01$; Fig. 5a). Of all months, August precipitation showed the strongest correlation ($r = 0.48$, $P < 0.01$) with PGP followed by May ($r = 0.45$, $P < 0.01$) and December ($r = 0.48$, $P < 0.01$). March through September precipitation was more strongly correlated ($r = 0.61$, $P < 0.01$) with PGP than crop yr precipitation (July through September; $r = 0.42$, $P < 0.01$). These results are consistent with Paulsen and Ares (1962) on the JER and previous studies by Beck et al. (2007) and Khumalo and Holechek (2005) on pasture 1.

Annual growth characteristics of black grama, dropseeds, and threeawns in the northern Chihuahuan Desert are discussed in detail by Paulsen and Ares (1962) and Beck et al. (2007). They both found black grama growth to be more highly associated with summer than total annual precipitation. Because dropseeds can grow under lower temperatures than black grama, they are more responsive to total annual rainfall, especially that occurring in the spring. Threeawns, which typically grow in mid to late spring, had a lower correlation with summer precipitation than either black grama or dropseeds (Beck et al., 2007). Nevertheless, threeawn production was better associated with summer than total annual precipitation (Beck et al., 2007).

For the 13-yr (2001–2014; 2002 excluded) period we used in NDVI-derived phenology analyses (Table S4; available online at <https://doi.org/10.1016/j.rama.2019.06.002>), annual peak NDVI was positively correlated with PGP ($r = 0.65$, $P = 0.02$). When the 3 yr with highest peak NDVI values (2006, 2008, and 2013) were excluded from the analyses, correlation between peak NDVI and PGP increased dramatically ($r = 0.80$, $P < 0.01$). The 3 yr with highest peak NDVI mentioned earlier exhibited the lowest spring and summer maximum ambient temperatures (see Table S1) and some of the highest annual rainfall values of the 13-yr series (see Table S1). It is possible that years with cooler spring and summer seasons and higher annual rainfall levels favor growth of C_3 shrubs and annual forbs and have limited effect on perennial C_4 grass growth. Browning et al. (2018) used the same approach used in this study to describe the green-up dynamics of shrub (mesquite) versus grass-dominated (tobosa grass) sites on the JER. They reported statistical differences between grass and shrub NDVI in 3 of the yr of their time series. NDVI in shrub-dominated sites tended to peak in May, whereas peak NDVI in grass-dominated sites occurred in late September to early October. In this study we were unable to segregate grass- versus shrub-dominated areas of P1, precluding the analytical approach used by Browning et al. (2018).

In contrast to precipitation, most ambient temperature correlations with PGP (52 yr) and peak NDVI values (13 yr) were negative (see Table S1; Figs. 4 and 5c). Mean maximum temperature for the May through September period showed the strongest negative correlation ($r = -0.52$, $P < 0.01$) with PGP (see Fig. 5b). Both mean and mean maximum temperatures for the months of July and August were significantly associated with declining PGP ($r = -0.45$, $P < 0.01$). Spring and summer (June–September) mean maximum temperatures were also strongly associated with declining peak NDVI ($r = -0.81$; $P < 0.01$, see Fig. 5c) during the 2001–2014 period. We note 1971, 1994, 2002, 2003, 2005, 2012, 2017, and 2018, which were yr with lowest PGP ($< 50 \text{ kg} \cdot \text{ha}^{-1}$), had above-average March through September maximum temperatures. Our results suggest that rising temperatures are increasingly suppressing

Figure 3. Change through time (2001–2014) in growing season start date (a) and end dates (b) and length of growing season (c) at our research site in the Chihuahuan Desert.

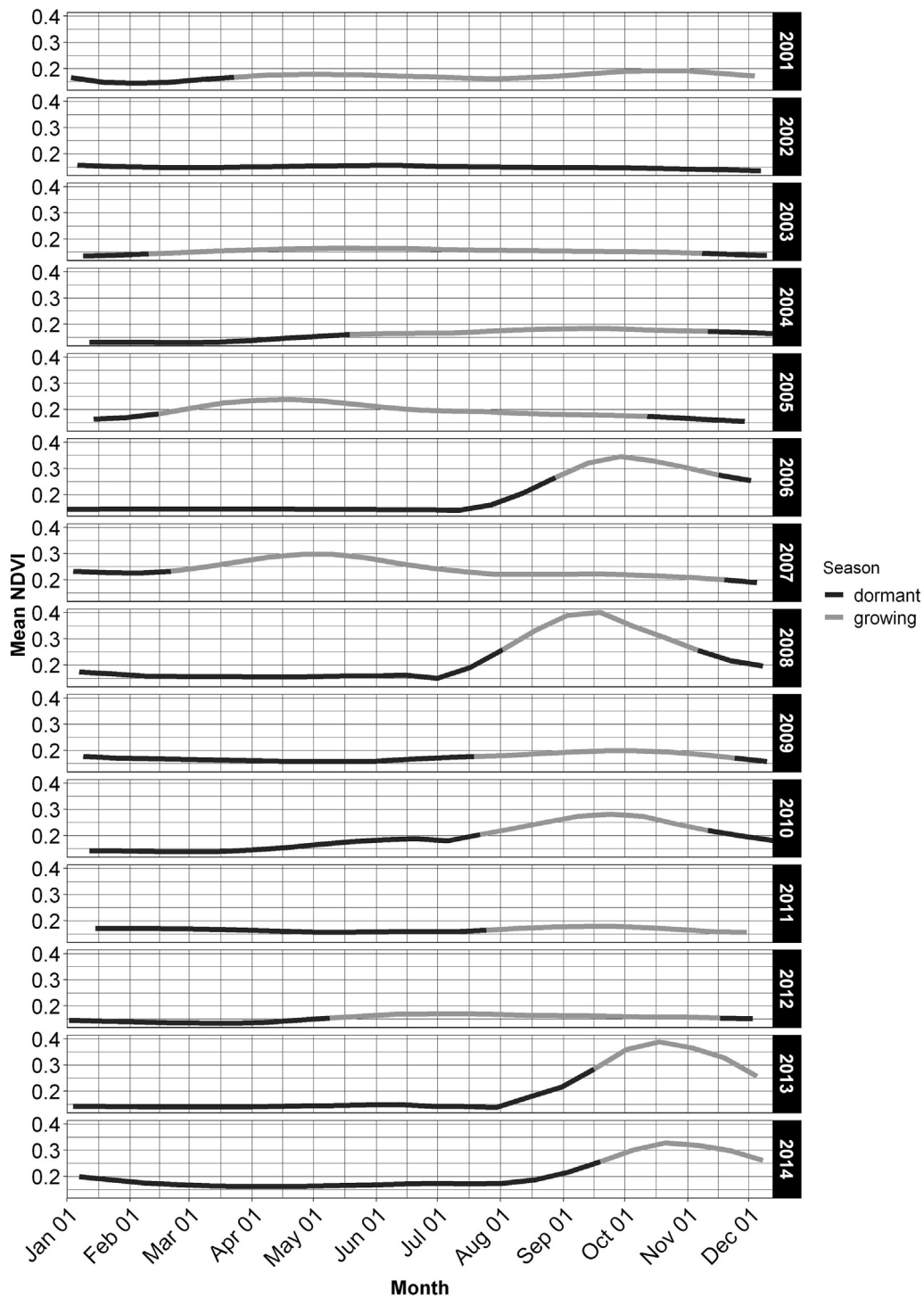


Figure 4. Seasonal changes in mean NDVI for our research site from 2001 to 2014. Light gray sections of the curve denote growing season for each year based on greenness phenometrics analyses.

perennial grass growth in years when precipitation is otherwise adequate for their growth to occur. We observed a significant precipitation-by-mean maximum temperature interaction effect ($P < 0.05$) on PGP (Fig. 6). Similar levels of precipitation were associated with decreasing PGP as mean maximum temperatures increased (see Fig. 6). Even mild temperature aberrations can adversely impact photosynthesis, and those that are extended and extreme can cause plant mortality (Derying et al., 2014; Hatfield and Prueger, 2015). Increased evaporation of soil moisture and disruption of soil microbial activity are other adverse impacts of

extreme temperatures on plant growth (Challinor et al., 2014; Derying et al., 2014; Bourne, 2015).

The strength of relationships between weather variables and PGP tended to decline in period 2 of this study (Table 2). For example, December through September precipitation was strongly correlated ($r = 0.84$, $P < 0.01$) with PGP in period 1, but this association became weaker in period 2 ($r = 0.50$, $P = 0.01$; see Table 2; Fig. 7a and b). The same trend was observed with other precipitation-related variables. Mean temperature characteristics showed no consistent correlations with PGP across the two periods

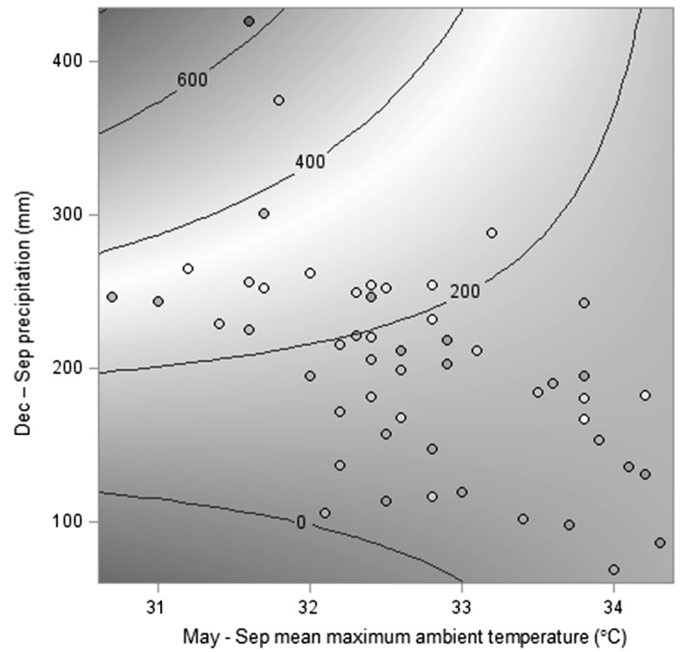
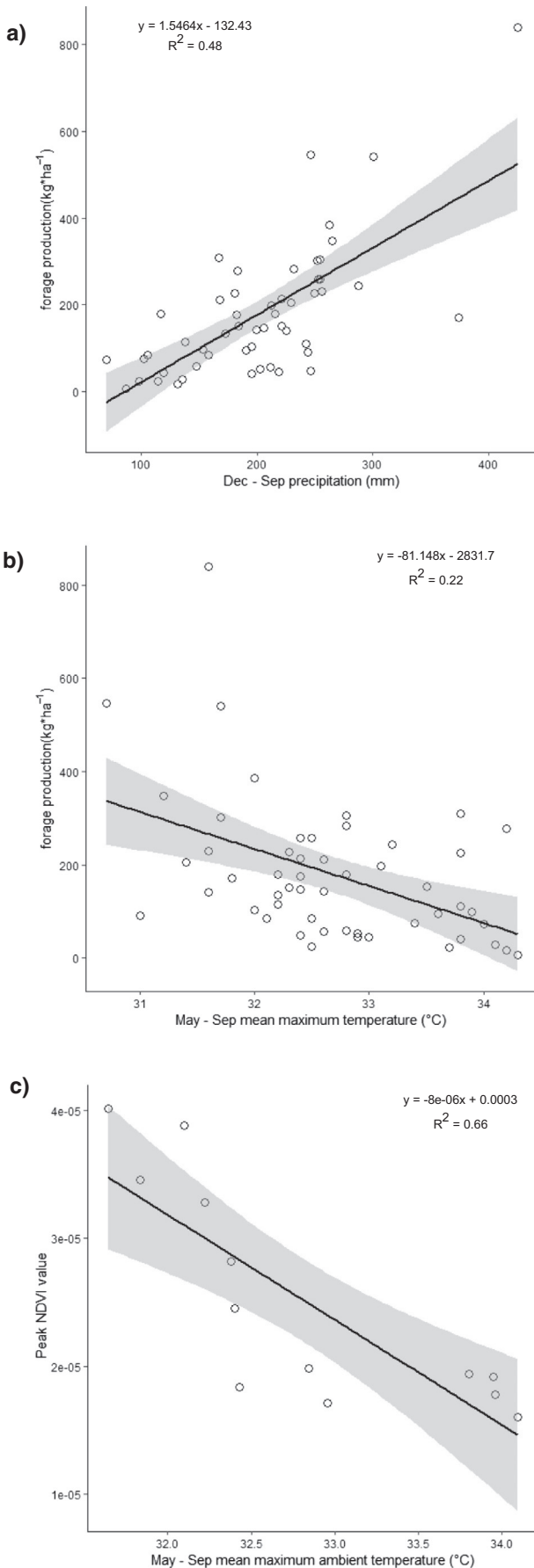


Figure 6. Contour fit plot of interaction ($P < 0.01$) effects of May through September mean maximum temperature ($^{\circ}\text{C}$) by December through September precipitation (mm) on forage production ($\text{kg}\cdot\text{ha}^{-1}$) at our research site.

Table 2

Coefficients of determination for forage ($\text{kg}\cdot\text{ha}^{-1}$) versus annual total precipitation (mm), mean annual ambient temperature ($^{\circ}\text{C}$), and mean annual ambient maximum temperature ($^{\circ}\text{C}$), for period 1 (1967–1992; $n = 26$) and period 2 (1993–2018; $n = 26$) of our study.

Season	Precipitation R^2		Mean maximum temperature R^2		Mean temperature R^2	
	Period 1	Period 2	Period 1	Period 2	Period 1	Period 2
Mar	—	0.15*	—	—	—	—
May	0.27**	—	—	—	—	—
Jun	—	0.16*	—	0.31**	—	0.22*
Jul	—	0.20*	—	0.17*	—	—
Aug	0.41**	—	—	—	—	—
Dec	0.24*	—	—	—	—	—
Annual	0.55**	0.18*	—	—	—	—
Crop yr (Jul–Sep)	0.23*	0.18*	—	—	—	—
Nov through Sep	0.56**	0.22*	—	—	—	—
Dec through Sep	0.68**	0.27**	—	—	—	—
Jan through Sep	0.59**	0.27**	—	—	—	—
Feb through Sep	0.55**	0.28**	—	—	—	—
Mar through Sep	0.52**	0.32**	—	0.21*	—	—
Apr through Sep	0.53**	0.30**	—	0.21*	—	0.16*
May through Sep	0.48**	0.34**	0.19*	0.17*	—	—
June through Sep	0.22**	0.32**	—	0.20*	—	—
Jul and Aug only	—	—	—	0.20*	—	—
Spring	0.30**	—	—	—	—	—
Winter	0.20*	—	—	—	—	—

* Significant at $P < 0.05$.

** Significant at $P < 0.01$.

(see Table 2). Conversely, spring and summer mean maximum temperatures were negatively associated with PGP in both periods. May through September ($r = -0.52$, $P < 0.01$, period 1; $r = -0.42$, $P < 0.05$, period 2) had the overall strongest negative associations with forage production (see Figs. 5c, 7c, and d).

Figure 5. Average forage production ($\text{kg}\cdot\text{ha}^{-1}$) at our research site in relation to: (a) December through September precipitation (mm); and (b) May through September mean maximum temperature ($^{\circ}\text{C}$) during the 52-year (1967–2018) study period. Peak NDVI at our research site in relation to (c) June–September mean maximum temperature ($^{\circ}\text{C}$) during the 14-year (2001–2014) MODIS-based analyses.

During the first half of our time series (period 1), December through September precipitation explained most of the variation in PGP. Increased temperatures in period 2 apparently reduced the predictive ability of precipitation (see Figs. 7a and b). Multiple regression equations using both precipitation and temperature variables explained roughly half of the yr-to-yr variation in PGP. The five best models had coefficients of determination (R^2) well below the 0.80 level we consider necessary for developing predictive tools (Table 3). Phenometric variables selected in our best models explained approximately three quarters of the yr-to-yr variation in PGP (2001–2014; Table 4). Variables such as green-up start date and initial NDVI value of the green-up curve (both occur in late spring or early summer) could be used to develop predictive tools

to aid ranchers in deciding whether conditions for early weaning are warranted.

Management Implications

Our results provide strong support for predictions from climate models regarding effects of warming temperatures for rangelands in the southwestern United States (Polley et al., 2013; Briske et al., 2015). Overall, PGP at our Chihuahuan Desert site declined by a mean average of 43% when comparing period two (1993–2018) with period one (1967–1992) of our 52-yr study. Over the recent past, growing seasons became shorter and tended to begin and end at progressively later dates. Our results are opposite to what was

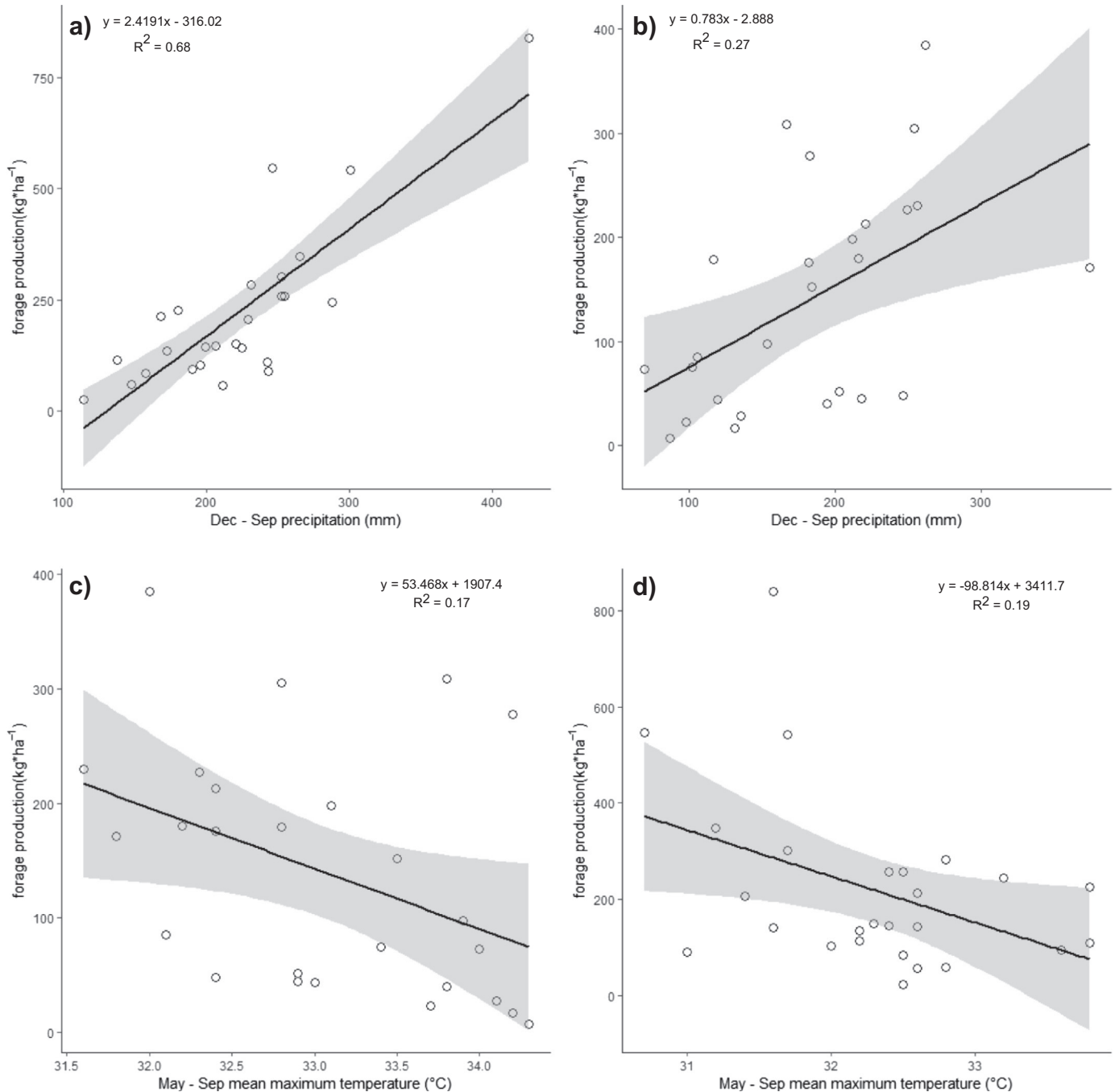


Figure 7. Average forage production ($\text{kg}\cdot\text{ha}^{-1}$) in relation to: (a, b) December through September precipitation and (c, d) May through September mean maximum temperature ($^{\circ}\text{C}$) for period 1 (a, c; 1967–1992) and period 2 (b, d; 1993–2018) at our research site in the Chihuahuan Desert.

Table 3
Multiple regression models using weather variables as predictors of forage production at our site (52-yr data set). Models were selected using Mallows C_p criterion-based method.

Number in model	R^2	C_p	Variables in model
4	0.61	4.79	Dec–Sep precipitation (+), previous yr's growing season precipitation (+), previous yr's July temperature (–), previous yr's August mean max. temperature (+)
4	0.60	5.24	Dec–Sep precipitation (+), previous yr's growing season precipitation (+), previous yr's July temperature (–), July mean max. temperature (–)
4	0.60	5.81	Dec–Sep precipitation (+), previous yr's growing season precipitation (+), previous yr's July temperature (–), June mean max. temperature (–)
4	0.60	5.87	Annual precipitation (+), Dec–Sep precipitation (+) previous yr's growing season precipitation (+), July mean max. temperature (–)
4	0.60	5.99	Annual precipitation (+), Dec–Sep precipitation (+) previous yr's growing season precipitation (+), previous yr's July temperature (–)

Table 4
Multiple regression models using phenometrics variables as predictors of forage production at our site (13-yr data set). Models were selected using Mallows C_p criterion-based method.

Number in model	R^2	C_p	Variables in model
4	0.75	3.87	Growing season start date (+), growing season end date (–), green-up rate (–), NDVI value at beginning of green-up (+)
4	0.75	3.93	Peak NDVI value (+), green-up rate (–), area under green-up curve (–), NDVI value at beginning of green-up (+)
4	0.75	4.05	Growing season end date (–), green-up rate (–), area under green-up curve (–), NDVI value at beginning of green-up (+)
4	0.79	4.36	Peak NDVI value (+), green-up rate (–), brown-down rate (–), area under green-up curve (–)
4	0.82	4.37	Growing season start date (+), peak NDVI value (+), green-up rate (–), brown-down rate (–)

recently reported by Augustine et al. (2018) for the northern Great Plains. In their manipulative 7-yr study, Augustine et al. (2018) reported a 38% increase in biomass production under conditions of increased CO₂ and ambient temperature. Interestingly, at this Wyoming site, a climate change–driven decrease in forage quality occurred. If these findings held true more generally for C₄ rangeland forage grasses, then ranchers in the desert southwest should anticipate a future with less and lower-quality forage. In addition, if yr-to-yr variation in rainfall (as documented in period 2 of this study) continues to grow, acceleration of shrub encroachment can be expected (Gherardi and Sala, 2015). Warming temperatures are likely to further exacerbate ranching challenges because in addition to conditions of forage decline, livestock will likely be exposed to augmented summer thermal stress. Thomas et al. (2015) reported that the average cow/calf producer in the Chihuahuan Desert raises ≈ 250 animal units per year (AUY) on 16,000–20,000 ha (≈ 16 times larger than our study area). A report by Hawkes (2004) on the financial returns for cattle reared in P1 (1997–2001) suggested a net return of \$2.31 • head^{–1}. The 43% mean reduction in PGP in our second 26-yr study period (1993–2018) means that ranchers who previously could raise 250 AUY in the late 1960s may now sustainably support only 150 AUY (meaning a long-term ranch-wide [total AUYs] net return reduction of > \$231 over a 52-yr time period). Sawalbah et al. (2019) corroborated a declining trend in statewide (New Mexico) cattle numbers since 1994 that was related to more variable precipitation, increased temperatures, and more frequent droughts. As these scenarios play out, the ranching industry will need to rapidly adopt innovation strategies to stay in business. One such strategy could include the use of specialized desert-adapted livestock genetics. Raramuri Criollo cattle from northern Mexico show remarkable abilities to cope with nutritional and thermal stresses of the Chihuahuan Desert (Anderson et al., 2015; Spiegall et al., 2019) and are being viewed as one of many possible solutions to adapt to a hotter and drier southwest. Stocking and risk management strategies for Chihuahuan Desert range livestock producers under conditions of climate change are provided by Torell et al. (2010), Thomas et al. (2015), and Sawalbah et al. (2019).

Acknowledgments

We acknowledge graduate students and faculty in the Department of Animal and Range Sciences at New Mexico State University

who worked meticulously collecting 5 decades' worth of data analyzed in this paper. We are thankful to the associate editor and two anonymous reviewers who provided comments that helped improve an earlier version of this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.rama.2019.06.002>.

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