



Foraging behavior of Raramuri Criollo vs. commercial crossbred cows on rangelands of the southwestern United States and Northern Mexico[☆]

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ARTICLE INFO

Keywords:

Heritage genetics
Beef cattle
Cow-calf
Animal agriculture
GPS tracking

ABSTRACT

Matching livestock genetics to climatically variable and nutritionally challenging environments is critical to the success of livestock ranching in the Southwest US, Northern Mexico, and arid rangelands elsewhere. We compared foraging behavior patterns of Raramuri Criollo (a heritage breed) and British beef cows at the Jornada Experimental Range (JER) in southern New Mexico, USA, and Rancho Experimental Teseachi (RET) in central Chihuahua, Mexico, during spring and fall of 2005. The study design comprised four animal monitoring weeks per site and season and each animal monitoring period consisted of four replicates, each of which included a set of six mature cows per breed equipped with a GPS tracking collar. GPS-derived movement, activity, and vegetation use variables were analyzed by sets of mixed models considering the fixed effects of breed, site, season, and all interactions (significance; $P < 0.05$). Compared to the British cows, Raramuri Criollo counterparts traveled further and grazed across larger areas of flat desert rangeland at JER and explored and grazed higher elevation rangelands with steeper slopes at RET. Breed differences were greatest when forages were dormant or scarce. Similarly, habitat use differed by vegetation class and breed with British cows spending more time in open grassland areas dominated by palatable herbaceous plants at JER and RET. Breed differences observed in this study likely reflected the outcomes of natural (Criollo) vs. artificial (British) selection pressure through time. Foraging behavior traits observed in Raramuri Criollo cows could be critical for adaptation of cow-calf production systems of the region to increasingly variable foraging environments caused by climate change.

1. Introduction

Extensive cattle ranching on arid rangelands of New Mexico (USA) and Chihuahua (México) usually involves allocation of heterogeneous pasture resources to animals over varying periods of time. Underlying this common practice is the assumption of proper grazing distribution which is vital for achieving efficient utilization of forage resources and minimizing rangeland degradation (Holechek et al., 2011). However,

compared with heritage cattle, modern beef breeds are generally less able to adjust their grazing behavior patterns to match the spatiotemporal heterogeneity of desert forages (Cibils et al., this issue; McIntosh et al. this issue). There is growing evidence that heritage genotypes, which are rarely shaped by artificial selection aimed at improving productivity traits, maintain similarities with homologous wild ungulates adapted to surviving in patchy rangeland ecosystems (Mysterud, 2010). Torell et al. (this issue) showed that higher profits can be achieved

[☆] This research is a contribution from the Long-Term Agroecosystem Research (LTAR) network. LTAR is supported by the United States Department of Agriculture. Partial funding was provided by the Facultad de Zootecnia y Ecología, Universidad Autónoma de Chihuahua. This manuscript is the result of collaborative international efforts at several institutions during the past decade as part of the Jornada LTAR program. Additional support was provided by the USDA National Institute of Food and Agriculture, SAS CAP Grant No. 2019-69012-29853.

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raising Raramuri Criollo (heritage cattle) vs. British crossbred cattle in the Chihuahuan Desert, due to more efficient use of desert forages and reduced input costs, mostly associated with less reliance on feed supplements. Modern beef cattle selection programs have increased weights and feed conversion efficiency of beef cattle (Raynor et al., 2021; Terry et al., 2021). This genetic change is thought to have increased the need for costly external feed resources (Diamond, 2002), placing additional strains on the very lean profit margins of typical family-owned cow-calf operations (Holechek and Hawkes, 1993). Family ranching across the region plays a critical role in maintaining working landscapes needed for the conservation of semiarid and arid ecosystems (Brunson and Hunt-singer, 2008). Therefore, adaptation strategies (such as raising heritage cattle genetics) aimed at preventing rancher attrition are of pivotal importance to the preservation of social-ecological rangeland systems on either side of the US-Mexico border.

In México, as in other countries of North and South America, heritage Criollo cattle populations originated and spread from the early African and Iberian cattle strains that were brought into the new continent by European explorers during the XIV century (Armstrong et al., 2022). However, these animals were gradually substituted and genetically absorbed by more specialized beef cattle breeds, relegating native Criollo cattle to small herds that have adapted to survive in remote and marginal regions with minimum or no artificial selection for modern production traits. There is growing evidence that close-to-natural selection operating on those isolated herds may have conferred Criollo cattle remarkable resilience and ability to reproduce in harsh environmental conditions with scarce or variable forage resources. These small herds remained under the ownership of traditional producers and indigenous communities and are now among the least genetically eroded heritage cattle biotypes (Hernandez Sandoval, 2001). One of those Criollo biotypes is the Raramuri Criollo (RC) cattle from the Sierra Tarahumara (Copper Canyon) in the state of Chihuahua, México (De Alba Martínez, 2011; Anderson et al., 2015), where it evolved in isolation for more than 400 years. Those herds developed on rugged terrain and steep slopes and under stressful nutritional conditions. Diets were made up predominantly of a variety of browse species, including several shrubs and small trees, cacti, and native herbaceous grasses and forbs largely limited in abundance due to low and erratic rainfall patterns and rising temperatures (De Alba Martínez, 2011). Those herds also developed with minimal prophylaxis (preventive veterinary care) through the use of modern husbandry practices and vaccines.

A group of 30 cows and three bulls of RC cattle of the Sierra Tarahumara region were introduced to the Jornada Experimental Range (JER) basin in Las Cruces, NM in 2005 (Estell et al., 2021). The goal was to establish a base herd on which to conduct foraging behavior and economics research comparing RC cattle with commercial crossbred beef cattle under Chihuahuan Desert conditions of south-central New México (Estell et al., 2021). At this time, a two-site, two-season, two-breed, one-year (2005) preliminary collaboration study with the Rancho Experimental Teseachi (RET), in the Central Northwest foothills of the State of Chihuahua, México, was established (Roacho Estrada et al., 2008). This pioneer study compared breeds in the hot, arid, and relatively flat Jornada basin in New Mexico and the temperate, semiarid (526 mm annual precipitation) and rugged (elevations from roughly 2000 to 2600 m) woodlands (Pinyon-Juniper-Bouteloua to Pine-Oak-Muhlenbergia communities) in the Sierra Madre foothills (Roacho-Estrada et al., 2008). Despite the considerable logistical complexity of moving equipment and personnel across an international boundary, by including two contrasting sites and seasons we were able to conduct a more robust comparison of breeds. This initial study spurred a series of subsequent research projects comparing grazing behavior of Raramuri Criollo and commercial crossbred beef cattle in the desert plains of southern New Mexico (Peinetti et al., 2011; Spiegel et al., 2019; Nyamuryekung'e et al., 2021a; 2021b, 2022). Although much has been learned since the study reported here was conducted (2005), this experiment set the foundation for a prolific line of climate

adaptation research conducted at multiple sites in North and South America (see Cibils et al., this issue).

The objective of this foundational study was to compare the grazing behavior and spatiotemporal patterns of rangeland use of RC (heritage) vs. British cattle breeds (Angus, Hereford and their crosses; AH). Because no experimental data were available at the time, we sought to describe foraging patterns of heritage vs. improved beef cows in relation to climate conditions, vegetation, forage availability and quality, distance to water, and elevation and topography in two contrasting pasture locations of the southwestern US and northwestern Mexico during spring and fall. Given differences in body weight, nutritional requirements, and natural selection background of tested breeds, we hypothesized that RC cows would adapt to limited forage quality and availability by: 1) exploring larger areas of the grazing pasture, traveling further, and using a wider array of vegetation types; and 2) spending less total time grazing, while traveling longer distances to explore areas of pasture that are either located further away from permanent water sources in a flat desert (JER) or located on steeper slopes and higher elevation mountain ranges (RET).

2. Material and methods

2.1. Study sites

The study was conducted at two experimental sites (Fig. 1), the Jornada Experimental Range (JER) and the Rancho Experimental Teseachi (RET), during spring and fall of 2005. The JER is located at the north end of the Chihuahuan Desert (32° 37' N; 106° 44' W), about 23 miles north of Las Cruces, New Mexico, United States, and includes 78,266 ha of relatively flat terrain (1300–1600 m). The climate and agroecological characteristics are typical of a hot desert with a mean annual precipitation of 247 mm, more than 50 percent of which occurs between July and September. Annual precipitation during the year when the study was conducted was 296 mm, above the long term average for the site. Mean ambient temperature is highest in June and lowest in January, averaging 36 and 13 °C, respectively (Wainwright, 2006). Mean maximum annual temperatures have increased in recent decades, especially in the years since 2012 (Mcintosh et al., 2019). This study was conducted in a 1160-ha pasture located near the JER head-quarter facilities (Fig. 1).

The RET is located in the eastern region of the Sierra Madre Occidental (28°48' N; 107°25' W), about 10 miles south from the Colonia Oscar Soto Máñez, Municipality of Namiquipa, Chihuahua, México. This site covers over 11,000 ha of a typical mountain rangeland site in central Chihuahua. The terrain altitude varies between 2058 and 2640 m and the dominant topography is characterized by light to steep slopes ranging from 1 to 89%. The climate is characterized by cold winters and hot summers. The long term (1991–2019) average annual precipitation is 526 mm and the average annual relative humidity is 60%. Mean ambient temperature is highest in June and lowest in December, averaging 26 °C and 10 °C, respectively. The comparative grazing study was carried out in a 2550 ha pasture located on the southern side of the RET (Fig. 1). Annual precipitation during the year when the study was conducted was 467 mm, below the long term average for the site. Mean maximum annual temperatures have increased steadily in the years since 2010 (Rancho Teseachi, unpublished weather records). However, overall the JER site was warmer and drier compared to the RET site. Monthly average precipitation and temperature recorded the year before and during the study year at the two sites is presented in Fig. 1.

Pastures at the two experiment sites (JER and RET) had contrasting biotic and abiotic characteristics which are known to affect both forage and livestock production. Whereas JER is a typical hot desert rangeland with flat terrain and long distances to permanent water sources, water distance rarely represents an impediment at RET, but steep slopes and high elevation terrain may impair livestock grazing distribution at this site (Suppl. Mat., Table S1). The study was conducted in the same

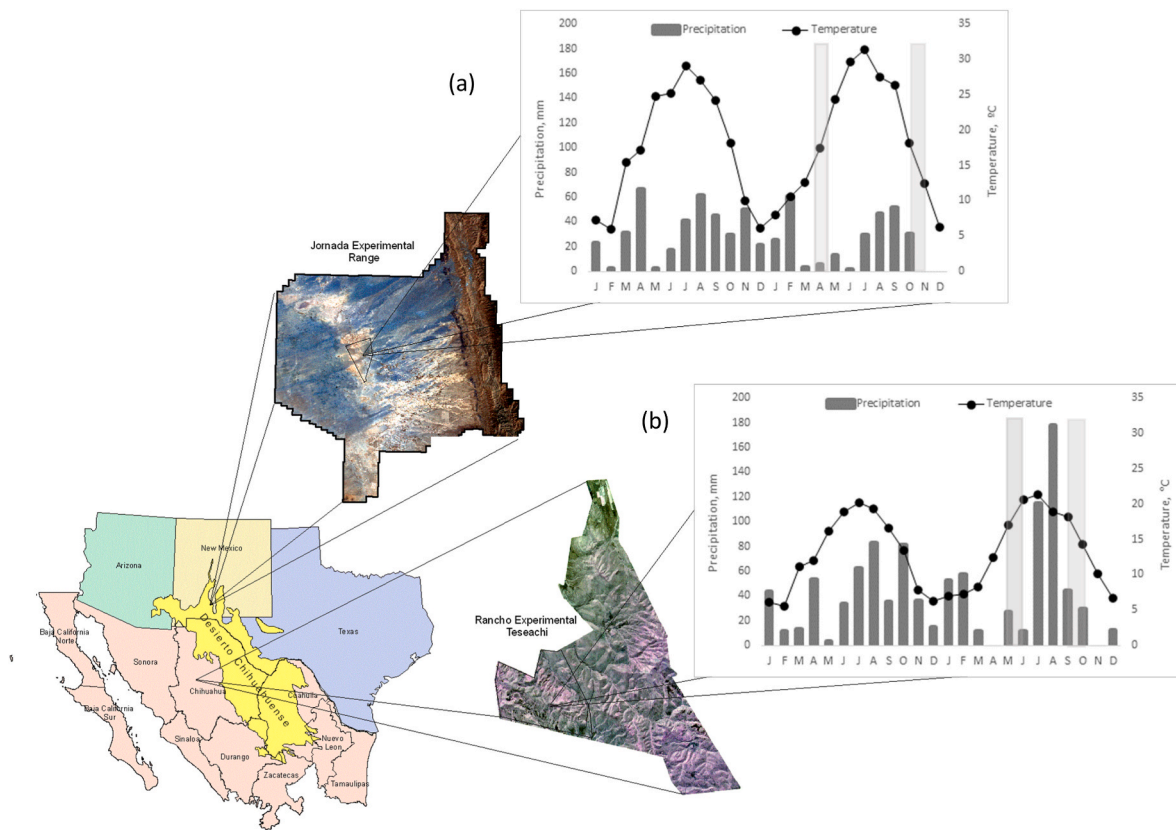


Fig. 1. Geographic location and mean monthly precipitation and air temperature recorded during 2004 and 2005 at our study sites in (a) New Mexico, USA, and (b) Chihuahua, Mexico. Superimposed bars indicate cattle monitoring periods at each site.

pastures during spring and fall of 2005. The pastures were grazed by cattle only during the experiment periods (shown in Fig. 1) and were rested (i.e. no cattle were present) the remainder of 2005. Study pastures at both sites were only grazed with collared animals ($n = 12$) during the 8-week monitoring period (4 weeks per season), therefore stocking rates were approximately 48 ha per AUM (Animal Unit Month) at JER and 106 ha per AUM at RET. During the experiment period, estimated forage allowance (forage mass per cow) at JER and RTE was 60.9 and 100.4 tons/animal, respectively, in spring and 49.6 vs. 114.1 tons/animal, respectively, in fall. Prior to this experiment, the study pasture at JER

had been managed with a light stocking rate ($<$ recommended 30% forage removal) and had been grazed seasonally during the dormant season over the previous five years. The pasture at RET had been rested (i.e. had received no cattle grazing) since 1997 and was managed with a light stocking rate ($<$ recommended 50% forage removal) due to grazing capacity limitations associated with the presence of steep slopes across a large proportion of the pasture (Suppl. Mat., Table S1). At both sites there was a single permanent water point and animals were supplied with a choice of mineral and salt supplements.

Vegetation at JER is dominated by honey mesquite (*Prosopis*

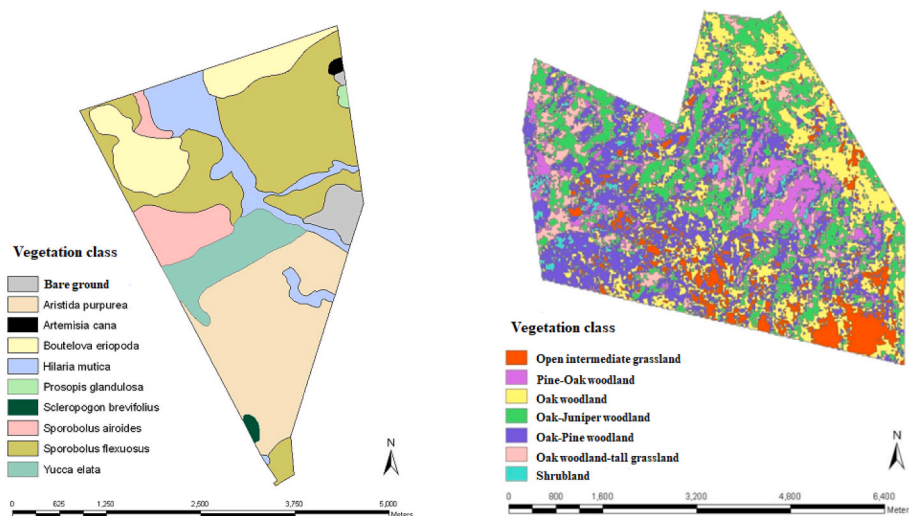


Fig. 2. Vegetation maps of study pastures used for analyses of vegetation selectivity by Raramuri Criollo vs. Angus or Hereford cattle at the Jornada Experimental Range, in New Mexico, United States (left), and Rancho Experimental Teseachi, in Chihuahua, Mexico (right).

glandulosa Torrey) intermixed with perennial grasses dominated by black grama (*Bouteloua eriopoda*), dropseeds (*Sporobolus* spp.) and threeawns (*Aristida* spp.). Soap-tree yucca (*Yucca elata*) and broom snakeweed (*Gutierrezia sarothrae*) are common subdominant plant species. Lowland grasslands dominated by tobosa (*Pleuraphis mutica*) and burrograss (*Schleropogon brevifolius*) occur on soils with high clay content (Gibbens et al., 2005). Ten vegetation clusters were identified and analyzed at JER. These vegetation classes were determined from early vegetation maps developed by Gibbens et al. (2005) constructed from a combination of high-resolution aerial photography and field surveys of most dominant plant species (Fig. 2). Map development details are provided by Peinetti et al. (2011).

Vegetation at RET includes a combination of oak and pine woodlands, tall grasslands dominated by a combination of *Muhlenbergia* spp. (*Muhlenbergia emersleyi*, *Muhlenbergia montana* and *Muhlenbergia rigida*), blue gramma (*Bouteloua gracilis*) and lobero grass (*Licurus phleoides*). Junipers (*Juniperus* spp.) are also common on slopes. Seven vegetation classes were identified and analyzed at RET. These vegetation classes were defined previously by Favela (2003) using a combination of Landsat TM 5 imagery, digital elevation models, and field surveys of dominant plant species (Fig. 2).

2.2. Forage sampling

Stratified forage samples of most dominant plant species were collected across each site, vegetation class, and season by clipping 1 × 1 m quadrats to ground level. A total of 100 and 211 samples were collected at JER and RET, respectively. Samples were oven dried at 60 °C for 48 h and weighed, and dry weights were used to estimate a weighted mean of forage mass to calculate total forage availability of most dominant plant species in each vegetation class, season, and site (Table 1).

Table 1

Vegetation classes, dominant plant species and seasonal herbage mass in a grazed rangeland pasture at the Jornada Experimental Range, in New Mexico, United States, and Rancho Experimental Teseachi, in Chihuahua, Mexico.

| N | Class | Area (ha) | Spring ^a | | | | Fall | | | |
|---|-------|-----------|---------------------|-------------|--------------|------------|-------------|-------------|--------------|------------|
| | | | D1 (%) | D2 (%) | D3 (%) | HM (kg/ha) | D1 (%) | D2 (%) | D3 (%) | HM (kg/ha) |
| Jornada Experimental Range ^b | | | | | | | | | | |
| 1 | SPFL | 366 | BOER (28.9) | GUSA (18.6) | SPFL (15.6) | 516.4 | GUSA (42.8) | ARPU (18.9) | BOER (14.1) | 416.2 |
| 2 | ARPU | 325 | BOER (24.8) | PLMU (18.1) | GUSA (16.2) | 690.9 | BOER (27.9) | GUSA (18.9) | PLMU (15.1) | 519.1 |
| 3 | BOER | 141 | BOER (40.7) | SCBR (21.1) | PLMU (18.5) | 442.7 | BOER (58.7) | GUSA (18.0) | SPCR (9.2) | 612.9 |
| 4 | PLMU | 130 | BOCU (31.9) | PAOB (22.4) | ANUAL (19.9) | 910.7 | PLMU (64.0) | SCBR (16.5) | SPCR (12.9) | 925.2 |
| 5 | YUEL | 98 | BOER (33.4) | SPCR (24.8) | ANUAL (22.6) | 1036.3 | BOER (55.0) | SPCR (28.9) | ARPU (12.7) | 480.3 |
| 6 | SPAI | 81 | PLMU (50.8) | SCBR (16.6) | ARPU (14.4) | 508.0 | PLMU (56.5) | SPCR (21.7) | SCBR (13.6) | 397.6 |
| 7 | BARE | 37 | ANUAL (54.2) | SCBR (28.3) | CRPO (10.2) | 161.0 | – | – | – | – |
| HM Weighted Average (kg/ha) | | | | | | 630.8 | – | – | – | 515.3 |
| Rancho Experimental Teseachi ^{d,e} | | | | | | | | | | |
| 1 | OPW | 673 | MUEM (36.7) | MUMO (12.5) | MURI (10.8) | 496.8 | MUMO (15.0) | MURI (10.9) | MUEM (9.9) | 580.0 |
| 2 | OW | 581 | MUEM (20.9) | MURI (11.0) | BOGR (10.7) | 412.2 | MUMO (14.5) | MURI (13.9) | LIPH (13.8) | 580.4 |
| 3 | OJW | 553 | MUEM (22.1) | MUMO (13.3) | ARAR (8.8) | 495.9 | MUMO (17.3) | MURI (14.0) | LIPH (12.8) | 534.2 |
| 4 | OWTG | 247 | MUEM (26.4) | MUMO (24.7) | MURI (16.7) | 703.8 | MUEM (23.5) | MUMO (19.3) | MURIG (17.0) | 509.8 |
| 5 | IG | 228 | MURI (21.2) | MUMO (14.2) | BOGR (12.4) | 446.1 | MURI (24.3) | BOGR (17.9) | MUMO (16.18) | 537.0 |
| 6 | POW | 191 | MUEM (56.8) | MUMO (17.1) | SCSC (12.5) | 302.4 | MUMO (27.4) | MURI (16.3) | MUEL (13.3) | 316.6 |
| 7 | SH | 67 | MURIG (43.9) | MUMO (34.6) | SCSC (14.7) | 265.4 | MUMO (44.3) | MUEM (35.1) | BRAN (8.07) | 455.8 |
| HM Weighted Average (kg/ha) | | | | | | 472.1 | – | – | – | 536.4 |

^a D1 = First dominant species, D2 = Second dominant species, D3 = Third dominant species, HM = herbage mass.

^b Following Gibbens et al. (2005) grassland and shrubland vegetation classes 1–7 were named according to the second most dominant plant species as: *Sporobolus flexuosus* (SPFL), *Aristida purpurea* (ARPU), *Bouteloua eriopoda* (BOER), *Pleuraphis mutica* (PLMU), *Yucca elata* (YUEL), *S. airoides* (SPAI), barren areas with high percent bareground (BARE), Annual plants (ANUAL).

^d Following Favela (2003) woodland and grassland vegetation classes 1–7 were classified using the most dominant plant species as: Oak-Pine Woodland (OPW), Oak Woodland (OW), Oak-Juniper Woodland (OJW), Oak woodland-tall Grassland Savanna (OWTG), Intermediate Grassland (IG), Pine-Oak Woodland (POW), Shrubland (SH).

^e *Aristida arizonica* (ARAR), *Bouteloua gracilis* (BOGR), *Licurus phleoides* (LIPH), *Muhlenbergia montana* (MUMO), *Muhlenbergia emersleyi* (MUEM), *Muhlenbergia rigida* (MURI), *Muhlenbergia rigens* (MURIG), *Muhlenbergia eludens* (MUEL), *Schyzachirium scoparium* (SCSC).

2.3. Animal monitoring

All animal handling procedures were approved by the Institutional Animal Care and Use Committees in New Mexico (New Mexico State University IACUC) and Chihuahua (Universidad Autónoma de Chihuahua IACUC), respectively. Phenotypically and genotypically divergent groups of heritage Raramuri Criollo cattle and commercial British cattle breeds and their crosses were used. The commercial breeds (Angus, Hereford and their Hereford x Angus crossbreeds [AH]) were raised and developed within each site and were therefore adapted to the predominant environmental conditions and management at each site. Heritage Raramuri Criollo cattle (Armstrong et al., 2022) used at JER originated from animals that were brought from warm and dry regions of the low Sierra Tarahumara, in Chihuahua, México (Anderson et al., 2015), whereas the RC cattle used at RET originated from animals that were brought from cool and wet regions of the high Sierra Tarahumara, in Chihuahua, Mexico. So due to different origin, environment, and management conditions, body weight of cows varied between breeds and sites. The weight of AH and RC cows at JER was 567.2 ± 57.3 and 329 ± 23.6 kg, respectively. The weight of AH and RC cows at RET was 426 ± 35.2 and 271 ± 47 kg, respectively. At both experimental sites, cows were in mid-to-late gestation during spring and in a mid-to-late lactation phase during the fall. All cows were treated with 1 ml of IVERMAX® per 10 kg of live weight to control internal and external parasites.

Six cows of each breed, 12 total, were monitored at each site. The spring monitoring season took place from April 2 to 30 and May 7 to June 4, 2005 at JER and RET, respectively. The fall monitoring season took place from October 22 to November 19 and September 17 to October 15, 2005 at JER and RET, respectively. Study animals were fitted with collars equipped with a GPS and a biaxial motion sensor (Lotek 2200; Lotek, Newmarket, ON, Canada) programmed to log and store location data at 5-min intervals. The collars were tightened properly to the cow's neck to minimize erroneous motion sensor records (Moen et al., 1996; Turner et al., 2000).

After retrieval, collar data were differentially corrected by location, using base station reference data from New Mexico State University, Las Cruces, New Mexico, USA for JER and the Instituto Nacional de Estadística, Geografía e Informática (INEGI), Chihuahua, México for RET. Differential corrections were conducted using the N4 V1, 1985 software (LoteK, Newmarket, ON, Canada) that corrected GPS positions to within 4.5 m of true locations. The Home Range Extension tool (Rodgers et al., 2005) for ArcMap (ESRI, 2000) was used to convert raw GPS data to geographic coordinates using the Universal Transverse Mercator format with the North American Datum of 1983 (NAD 83) projection system for the zone 13 N. Converted data were expressed in meters to facilitate algebraic derivation of traveling distance and explored polygons and grazing areas.

Some GPS collar data were lost due to: 1) GPS unit initialization failures; and 2) poor satellite signal reception associated to the topography (D'Eon et al., 2002) and type (Moen et al., 1996) and density (D'Eon et al., 2002) of vegetation cover. The criteria for managing missing GPS records was as follows: 1) when no position coordinates registered for periods <2 h and the y-axis motion sensor was <10 units (0 = no movement; 255 = maximum movement), it was assumed that the cow was resting on a site with reduced satellite signal and the last registered coordinate position was considered valid; 2) otherwise, when the y-axis motion sensor was >10 units and GPS unit did not register coordinates for a maximum of 30 min, it was assumed that the cow was grazing following a linear path and linear interpolation was used to determine the missing animal locations; 3) when the y-axis motion sensor was >10 units and there were no GPS positions for periods >30 min, random positions were determined for the block of six missing positions; and 4) data from the whole day were discarded when a GPS unit lost 5 consecutive hours of GPS data. The resulting database had a median of 5 cows per week, site, breed and season from which GPS data were retrieved (288 points per day), processed and analyzed. Across sites, breeds, seasons, and weeks the median for complete cow daily GPS datasets was 94%.

Following Ganskopp and Bohnert (2006) and Ungar et al. (2005), animal positions were classified into grazing, resting and traveling activities, using a combination of motion and animal location data recorded by the GPS collar. Accelerometers yielded unitless numbers between 0 (no movement) and 255 (maximum movement) at 5 min intervals. Activity classification criteria used were the following: 1) when the motion index triggered by the left/right motion sensor was \geq the 55th percentile and the distance from the previous GPS positions was \leq 5 m, the activity associated with that position was recorded as "Resting"; 2) When the motion index triggered by the left/right motion sensor was \leq the 55th percentile and the distance from the previous GPS position was \geq 5 m, the activity associated to that position was recorded as "Grazing"; and 3) When the distance from a previous position was \geq 106.5 m, the activity associated to that position was recorded as "Traveling" (Ungar et al., 2005). The relative accuracy of this classification method has been described in detail by Ungar et al. (2005) and Augustine and Derner (2013). Time allocated to each activity was computed by adding the number of GPS points classified as grazing, traveling, or resting and multiplying that number by the time interval between points (5 min).

A digital elevation model (DEM) with resolution of 27 m-pixel was used to provide an elevation and slope for each cow GPS position using ArcGIS 9.1 software (ESRI, 2000). Both the daily average elevation and slope and the maximum elevation and slope, were calculated for each cow and analyzed only for the RET site because variability for slope and elevation was marked at RET but almost absent at JER (Suppl. Mat., Table S1).

Average Daily distance to water was calculated by recording the distance of every animal position to the permanent watering point. Total daily distance traveled was calculated by adding up the step size or distance between consecutive animal locations for a complete day. Movement velocity for each animal position was calculated and expressed as m/min. Daily time spent near the permanent water point

was calculated by counting the daily number of animal positions within a 100 m-buffer zone defined around the permanent water source. All calculations were conducted in MS Excel and ArcMap (ESRI, 2000).

The daily area explored by animals was estimated using the Kernel Adjusted Method (KAM), available with the Home Range extension of ArcMap software (ESRI, 2000). This method uses a distribution function to calculate the area density. The probability estimations were at 50 and 95%, where the KAM at 95% (KAM95) estimates the total area explored and KAM at 50% (KAM50) can be inferred to be grazing areas that receive more intensive use (e.g., preferred areas for grazing and resting). One advantage of KAM is that it is a non-parametric method and not influenced by the pixel size (Silverman, 1986). Finally, The GPS positions classified as grazing and resting were used to estimate the amount of time cows spent within each vegetation class (i.e., number of GPS locations classified as grazing and/or resting within each vegetation class).

Diet samples were collected from four Angus and three Hereford cannulated cows at JER and RET, respectively. Collections were conducted during the second and third week of each study season, coincident with the collection of forage samples. Following Lesperance et al. (1960), the rumen contents of four Angus cannulated cows at JER and three Hereford cannulated cows at RET were evacuated, stored into sealed plastic containers, and walls of the rumen were cleaned with sponges. Thereafter, cannulated cows were returned to the pasture and were allowed to graze for 45 min on representative grazing areas determined by inspection of GPS data of cows in the previous two weeks of the study. Finally, cows were returned to the corral, fresh boluses of ingested plant material were removed and placed in a sealed plastic bag, and rumen contents returned to the cows. The ingested forage samples were placed on a container with ice and transferred for storage to a -20°C freezer. Samples were thawed, dried at 60°C , ground, and analyzed for dry matter (DM) and crude protein (CP) by the Kjeldahl method (AOAC, 1980) and neutral detergent fiber (NDF) and acid detergent fiber (ADF) following procedures described by Goering and Van Soest (1970). Diet characteristics are detailed in Suppl. Mats. Table S2.

2.4. Experimental design and statistical analysis

The treatment design consisted of a $2 \times 2 \times 2$ factorial arrangement with two breeds (RC and AH), two sites (RET and JER) and two seasons (Spring and Fall). Within each breed-site-season subclass, a different set of six mature cows from each of the respective RC and AH herds was randomly selected per week and tracked daily for six days to monitor their grazing behavior. The process was repeated for four consecutive weeks at each study site and season. Animals of both breeds grazed simultaneously within the same pasture at each site to ensure the same exposure to environmental and management conditions for both genotype groups. This design was decided following the work by Koppa (2007) indicating a lack of social interaction between groups of different cattle breeds when they were group grazed in a large pasture at very low stocking rates.

Animal activity and distribution variables were analyzed using ANOVA. Three candidate linear mixed models were tested for goodness of fit with the MIXED procedure of SAS (SAS Inst. Inc., Cary, NC), to somehow account for the unbalanced structure of final datasets associated with missing data points for cows and/or days within a week when computing the F-tests of ANOVAs and, at the same time, quantify the relative importance of the subsampling variation explained by these two factors. The fixed common effects included site, season and breed, and all two- and three-factor interactions. The random effects considered by models were: **Model 1**, week(breed x site x season) which was considered the experimental unit and mean square error term in the F statistics to test fixed effects; **Model 2**, same as Model 1 plus cow(week x breed x site x season); and **Model 3**, same as Model 2 plus day(week x site x season). All variance components were estimated by the Restricted Maximum Likelihood (REML) method and likelihood ratio tests were

used to compare the goodness of fit of nested models (Model 2 vs Model 3 and Model 1 vs Model 2; Dobson and Barnett, 2018). Once the “best model” was selected, a “contrast statement” was used to test differences between the breeds within each site and season. The determination of degrees of freedom for F-tests was conducted by the Satterthwaite method, which is intended to produce an accurate F-test approximation when variance components for random effects are fitted. Response variables related to elevation and slope of terrain at RET were analyzed by the three linear mixed models described above, but excluding the main fixed effect of site and all corresponding interactions with that factor.

For vegetation class use analysis, daily grazing and resting time (h/d) were averaged per week within breed, season and site and analyzed within vegetation class for each study site. A mixed linear model that included fixed effects of breed, season and their interaction, and the random effect of week within breed by season as the error term was adjusted. A “contrast statement” was used to test differences between the breeds within each season. Differences were considered statistically significant at $P \leq 0.05$.

3. Results

3.1. Seasonal variation in forage biomass and diet quality

Spring was the season with most and least herbaceous forage availability (herbage mass; HM) at JER and RET, respectively (Table 1). The opposite occurred in the fall (Table 1). Seasonal difference in herbaceous forage availability (most-least biomass) was twice as large at JER (Spring vs. Fall HM = 115.5 kg/ha difference) vs. RET (Fall vs. Spring HM = 64.2 kg/ha difference). Diet quality parameters were numerically greater in Spring vs. Fall at JER (Suppl. Mat. Table S2). The opposite occurred at RET (Table S2). Once again, seasonal differences (highest – lowest percentage) for all three diet quality parameters was greater at JER (Spring vs. Fall: CP = 4.1% difference; NDF = 9.3% difference; ADF = 3.9% difference) than at RET (Fall vs. Spring: CP = 3.4% difference; NDF = 4.2% difference; ADF = 0.6% difference).

3.2. Model fitting

Likelihood ratio tests indicated a significant ($P < 0.01$) lack of fit of parsimonious Models 1 and 2 compared to the complete Model 3. The major advantage of Model 3 over other models was the further partition of variance components associated with the nested effect of day, which as a proportion of the residual variance of Model 3 was 0.31–0.94 for animal movement and activity budget variables (Suppl. Mat., Table S3), 0.65 to 0.96 for animal distribution variables (Suppl. Mat., Table S4) and 1.3 to 2.9 for variables associated with slope and elevation (Suppl. Mat., Table S5). Furthermore, the variance associated with the nested effect of cow was low and almost null for some animal movement (movement velocity) and activity budget variables (grazing and resting time; Suppl. Mat. Table S3) but was almost twice as large for average slope (Suppl. Mat., Table S5).

The statistical Model 3 showed that the variability between animals within the same breed and season was insignificant or near zero. Consequently, differences in animal behavior between individuals of the same genotype group were lower than the differences between animals of different genotypes. Thus, genotype or breed constituted an important source of variation, as was originally hypothesized.

3.3. Animal movement and activity budget

A three-way interaction between site, season and breed was detected for distance traveled, traveling time, and resting time, but not for movement velocity or grazing time (Table 2). RC cows dedicated more time to travel and traveled longer daily distances than the AH cows during fall at JER, and a similar trend was observed during spring at RET

Table 2

Movement, activity budgets, and spatial distribution of Raramuri Criollo (RC) and Angus, Hereford and their cross (HA) cows, during spring and fall at the Rancho Experimental Teseachi (RET) and Jornada Experimental Range (JER). Spatial distribution variables included maximum distance to the water source, and dispersal of clustered points in space as described by the minimum convex polygon (MCP) and home range as estimated by the 50 and 95% Kernel methods.

| Variable | Breed | RET | | JER | | Three-way Interaction P-value |
|-------------------------------|-------|----------------|---------------|--------------|----------------|-------------------------------|
| | | Spring | Fall | Spring | Fall | |
| Distance Traveled (km/d) | AH | 5.4 ± 0.56 a | 4.6 ± 0.55 | 9.6 ± 0.55 | 7.9 ± 0.55 a | 0.02 |
| | RC | 6.7 ± 0.56 b* | 4.5 ± 0.55 | 10.3 ± 0.55 | 10.8 ± 0.54 b | |
| Mov. Velocity (m/min) | AH | 4.9 ± 0.19 | 4.7 ± 0.18 | 7.2 ± 0.18 a | 5.9 ± 0.18 a | 0.23 |
| | RC | 5.2 ± 0.18 | 5.0 ± 0.18 | 7.7 ± 0.18 b | 7.0 ± 0.17 b | |
| Grazing time (h/d) | AH | 11.7 ± 0.23 a | 10.9 ± 0.21 a | 9.9 ± 0.21 a | 10.3 ± 0.21 a | 0.73 |
| | RC | 10.9 ± 0.22 b | 10.1 ± 0.22 b | 9.3 ± 0.21 b | 9.5 ± 0.21 b | |
| Resting time (h/d) | AH | 11.6 ± 0.21 | 12.7 ± 0.19 a | 12.0 ± 0.20 | 12.3 ± 0.19 | <0.05 |
| | RC | 11.9 ± 0.20 | 13.6 ± 0.20 b | 12.1 ± 0.19 | 11.9 ± 0.19 | |
| Traveling time (h/d) | AH | 0.7 ± 0.20 a | 0.4 ± 0.19 | 2.1 ± 0.19 a | 1.5 ± 0.19 a | 0.03 |
| | RC | 1.2 ± 0.19 b** | 0.4 ± 0.19 | 2.6 ± 0.19 b | 2.6 ± 0.19 b | |
| Maximum dist. To water (km/d) | AH | 2.1 ± 0.41 | 0.76 ± 0.40 | 3.4 ± 0.40 | 2.9 ± 0.40 | 0.81 |
| | RC | 2.2 ± 0.40 | 0.78 ± 0.36 | 4.1 ± 0.40 | 3.8 ± 0.40 | |
| MCP (ha) | AH | 55.6 ± 43.8 | 27.6 ± 43.0 | 203.8 ± 43.1 | 173.7 ± 43.1 a | 0.03 |
| | RC | 127.9 ± 43.5 | 26.9 ± 43.2 | 244.6 ± 43.1 | 410.9 ± 42.8 b | |
| 95% Kernell (ha) | AH | 123.5 ± 76.3 | 39.5 ± 75.0 | 381.1 ± 75.1 | 330.6 ± 75.0 a | 0.02 |
| | RC | 226.8 ± 75.9 | 38.7 ± 75.2 | 456.7 ± 75.0 | 795.4 ± 74.5 b | |
| 50% Kernell (ha) | HA | 29.3 ± 14.7 | 9.0 ± 14.4 | 84.7 ± 14.4 | 66.8 ± 14.4 a | 0.01 |
| | RC | 47.7 ± 14.6 | 8.6 ± 14.4 | 97.3 ± 14.4 | 157.0 ± 14.3 b | |

Different letters indicate statistically significant difference between the RC and HA breed groups within site and season (t -test $P < 0.05$). Asterisks indicate a trend toward statistical difference (* $P = 0.07$; ** $P = 0.08$). The three-way interaction was significant ($P < 0.05$) for six of the nine variables in this Table. For resting time, the breed mean difference in favor of the RC breed vs HA was greater in the Fall season than in the Spring at the RET site, while at JER that difference was greater in the Spring than in the Fall. The opposite was true for the other five variables with significant three-way interaction, with a greater mean for RC than for HA in the Fall compared to that for the Spring at RET, while at RET that difference was greater in the Spring than in the Fall. A two-way interaction of breed by site was observed for movement velocity. The mean was greater ($P < 0.05$) for RC than for the HA breed group at the JER site, but there was not difference ($P > 0.05$) between breed group means at RET.

(Table 2). RC cows dedicated more time to rest during the fall at RET (Table 2). Conversely, AH cows spent more time grazing than RC across sites and seasons. A two-way breed by site interaction was observed for movement velocity ($P < 0.05$), which indicated greater movement velocity of RC vs AH cows during spring and fall at JER (Table 2).

3.4. Animal spatial distribution and landscape use

Maximum distance to water varied by site and season ($P < 0.05$), being greater for JER vs. RET and in spring vs. fall (Table 2). A three-way breed by site by season interaction was observed for MCP and KAM50 and KAM90 estimates of daily home ranges explored by cows (Table 2). These variables were greater for RC vs. AH cows during the fall at JER (Table 2).

Differences in terrain use associated with spatial differences in average and maximum slope varied with breed and season, while differences in terrain use associated with spatial changes in elevation were observed between genotype groups at RET (Table 3). Use of higher elevation terrain with steeper slopes was greater for RC vs AH cows and for spring vs. fall. Compared to AH cows, the RC cows used higher elevation terrain in spring as noted by a significant season by breed interaction (Table 3).

Habitat use differed by vegetation class both at JER and RET (Table 4). At JER, AH and RC cows spent more time in *Aristida purpurea* (ARPU) desert grassland (Table 1). However, RC spent less ($P < 0.05$) time grazing (2.6 vs. 5.7 h/d) and resting (2.7 vs 6.5 h/d) in this vegetation class during fall compared to AH cows (Table 4). Conversely, in spring AH cows tended to graze longer (1.6 vs 1.1 h/d) in *Sporobolus flexuosa* (SPFL) desert grassland though the difference was not statistically detectable ($P = 0.19$; Table 4). In fall, RC cows grazed longer than AH counterparts (0.46 vs 0.03 h/d) in lowland *Sporobolus airoides* (SPAI) grassland containing a high density of tobosa grass but once again, the difference was not statistically detectable ($P = 0.23$; Table 4). At RET, cows spent more time in the open intermediate grassland (IG); RC cows spent a similar amount of time as did AH grazing in this vegetation class both during fall and spring ($P = 0.43$; Table 4). During spring, both genotypes spent less ($P = 0.003$) time resting in the intermediate grassland areas compared to fall (4.8 vs 10.2 h/d). During fall, both

Table 3

Average and maximum slope and elevation used by AH and RC during the spring and fall at the Rancho Experimental Teseachi in Chihuahua, Mexico.

| Variable | Breed | Season | | Breed Average |
|-----------------------|-------|--------------|--------------|---------------|
| | | Spring | Fall | |
| Average slope (%) | AH | 9.9 ± 0.67 | 8.4 ± 0.64 | 9.1 ± 0.46a |
| | RC | 12.4 ± 0.66 | 9.3 ± 0.65 | |
| Season Average | | 11.1 ± 0.59a | 8.8 ± 0.57b | |
| Maximum slope (%) | AH | 24.2 ± 2.47 | 18.2 ± 2.45 | 21.2 ± 1.74a |
| | RC | 34.3 ± 2.47 | 20.4 ± 2.45 | |
| Season Average | | 29.3 ± 2.09a | 19.3 ± 2.08b | |
| Average elevation (m) | AH | 2190.8 ± 4.4 | 2190.1 ± 4.3 | 2190.5 ± 3.1a |
| | RC | 2206.8 ± 4.4 | 2192.4 ± 4.4 | |
| Season Average | | 2198.8 ± 3.6 | 2191.3 ± 3.6 | |
| Maximum elevation (m) | AH | 2222.1 ± 6.5 | 2210.3 ± 6.3 | 2199.6 ± 3.1b |
| | RC | 2254.9 ± 6.4 | 2217.0 ± 6.4 | |

Breed * Season Interaction.

$P = 0.04$.

Means followed by different letters differ ($P < 0.05$) by breed or season main effects. Maximum elevation showed an interaction effect of breed by season so means of each effect are not reported.

breeds increased resting time in the intermediate grassland. Oak woodland (OW) was the second most preferred site (Table 4). No clear difference between breeds ($P = 0.79$) or season ($P = 0.1$) was observed in time spent grazing at this site, but both breeds spent more time ($P = 0.008$) resting in this site in spring vs. fall (4.5 vs 1.9 h/d). Oak-Pine woodland (OPW) and Oak-Juniper woodland (OJW) were used the least by both genotypes but RC cows spent more time grazing in both these vegetation types than did AH cows (Table 4).

4. Discussion

Overall, foraging behavior differences between RC and AH were greatest in the season with less forage available and lower diet quality (Fall at JER and Spring at RET). Breed differences appeared to be greater at JER where seasonal variation in forage quantity and quality were greatest. Compared to AH counterparts, RC cows traveled further and spent more time traveling, grazed shorter hours, and explored a larger area of the grazing pasture (at JER) during the season with lowest quantity and quality of available forages, partially supporting our hypothesis. Raramui Criollo cows at RET used higher elevation terrain and steeper slopes relative to AH cows. Breed differences in terrain use at RET were greatest during spring, the season with most forage restrictions. These findings are consistent with subsequent studies conducted at JER (Spiegel et al., 2019; Nyamuryekung'e et al., 2022) and elsewhere in the southwestern United States (Duni et al., this issue) that showed divergent foraging behavior during seasons with scarce forage. Criollo cattle showed greater ability to adjust their seasonal foraging behavior relative to British breed counterparts at both sites (Cibils et al., this issue).

Spatial distribution patterns of livestock on desert rangelands can be altered with breeds that are better adapted to local rangeland resources such that hotspots of intense use are avoided (Peinetti et al., 2011; Spiegel et al., 2019). Differences in foraging behavior observed at both study sites were likely the result of breed-specific selection pressures. Criollo genotypes were shaped by four centuries of adaptation to the rugged and heterogeneous semiarid ecosystems of the Sierra Madre of Chihuahua (Anderson et al., 2015) whereas British beef cows originated in relatively homogeneous and flat lowland pastures of the British Isles and have been intensely selected to produce heavier calves in production systems with few, if any, nutritional restrictions (Terry et al., 2021; Armstrong et al., 2022). Placement of water drinkers and rugged topography are two factors known to severely limit use of rangeland forages by cattle (Holechek et al., 1994). Nonetheless, Criollo cows in this study showed a superior ability to overcome both these constraints by traveling further from water (at JER, see further details below) and using steeper slopes and higher elevation terrain (at RET) compared to their British beef counterparts. At both study sites, the use of locally adapted cattle breeds, such as the RC, could provide a viable alternative to minimize undesirable environmental impacts of extensive animal agriculture, thus conserving rangeland vegetation and soils and supporting rancher livelihoods (Spiegel et al., 2020).

Regardless of genotype, animals traveled further, moved faster, and explored larger daily areas of the pasture at JER, a desert ecosystem with flat terrain and sparse forage and drinking water resources. Conversely, cows tended to move slower, travel shorter distances and explore smaller areas of the pasture at RET, a temperate woodland with more rugged topography where both forage and water availability were relatively more abundant. Placement of the permanent water point (middle of the pasture at RET vs. south end of the pasture at JER) may have also forced cows to travel further at JER vs. RET. Location of drinking water and preferred plant communities are both known to affect foraging decisions of livestock which ultimately result in observed spatial patterns of grazing distribution on rangeland (Valentine, 1947, 2001; Holechek et al., 1994). Still, despite site differences, RC traveled further and explored larger areas of the pasture than AH counterparts, particularly during the season when forages were dormant and/or

Table 4

Average time (h) that Angus x Hereford (AH) and Raramuri Criollo cows (RC) spent grazing and resting in each vegetation class during the spring and fall at the Jornada Experimental Range and Rancho Experimental Teseachi.

| Cover Class | Area (Ha) | Breed | Time Grazing (h) | | P-Value | | | Time Resting (h) | | P-Value | | |
|---|-----------|-------|------------------|-------------|---------|--------|-------------|------------------|-------------|---------|--------|-------------|
| | | | Spring | Fall | Breed | Season | Interaction | Spring | Fall | Breed | Season | Interaction |
| Jornada Experimental Range^a | | | | | | | | | | | | |
| SPFL | 366 | AH | 1.6 ± 0.2 | 2.2 ± 0.2 | 0.63 | <0.01 | 0.16 | 1.7 ± 0.2 | 2.7 ± 0.2 | 0.24 | 0.01 | 0.6 |
| | | RC | 1.1 ± 0.2 | 2.4 ± 0.2 | | | | 1.0 ± 0.2 | 2.4 ± 0.2 | | | |
| ARPU | 325 | AH | 5.0 ± 0.8 | 5.7 ± 0.8a | 0.11 | 0.29 | 0.07 | 5.6 ± 1.0 | 6.5 ± 1.0a | 0.19 | 0.16 | 0.03 |
| | | RC | 5.2 ± 0.8 | 2.6 ± 0.8b | | | | 6.6 ± 1.0 | 2.7 ± 1.0b | | | |
| PLMU | 130 | AH | 0.79 ± 0.3 | 0.37 ± 0.3 | 0.60 | 0.96 | 0.3 | 0.89 ± 0.5 | 0.43 ± 0.5 | 0.71 | 0.55 | 0.15 |
| | | RC | 0.18 ± 0.3 | 0.57 ± 0.3 | | | | 0.31 ± 0.5 | 1.31 ± 0.5 | | | |
| YUEL | 98 | AH | 1.3 ± 0.8 | 1.8 ± 0.8 | 0.62 | 0.41 | 0.86 | 1.8 ± 0.8 | 1.9 ± 0.8 | 0.72 | 0.72 | 0.83 |
| | | RC | 1.5 ± 0.8 | 2.4 ± 0.8 | | | | 1.9 ± 0.8 | 2.4 ± 0.8 | | | |
| SPAI | 81 | AH | 0.93 ± 0.2 | 0.03 ± 0.2 | 0.48 | 0.02 | 0.31 | 1.5 ± 0.4 | 0.12 ± 0.4 | 0.19 | 0.04 | 0.39 |
| | | RC | 0.85 ± 0.2 | 0.46 ± 0.2 | | | | 1.8 ± 0.4 | 1.1 ± 0.4 | | | |
| SCBR | 5 | AH | 0.12 ± 0.05 | 0.07 ± 0.05 | 0.36 | 0.77 | 0.5 | 0.28 ± 0.1 | 0.10 ± 0.1 | 0.75 | 0.75 | 0.42 |
| | | RC | 0.14 ± 0.05 | 0.16 ± 0.05 | | | | .10 ± 0.1 | 0.18 ± 0.1 | | | |
| PRGL | 4 | AH | – | – | 0.15 | 0.15 | 0.15 | – | – | 0.15 | 0.15 | 0.15 |
| | | RC | – | 0.43 ± 0.1 | | | | – | 0.95 ± 0.3 | | | |
| Rancho Experimental Teseachi^b | | | | | | | | | | | | |
| OPW | 673 | AH | 0.88 ± 0.1 | 0.76 ± 0.1 | 0.84 | 0.66 | 0.75 | 0.70 ± 0.4a | 0.47 ± 0.4 | 0.01 | 0.10 | 0.3 |
| | | RC | 0.80 ± 0.1 | 0.78 ± 0.1 | | | | 1.95 ± 0.4b | 1.02 ± 0.4 | | | |
| OW | 581 | AH | 3.8 ± 0.8 | 2.0 ± 0.8 | 0.79 | 0.10 | 0.76 | 4.7 ± 0.8 | 1.9 ± 0.8 | 0.79 | <0.01 | 0.72 |
| | | RC | 3.3 ± 0.8 | 2.0 ± 0.8 | | | | 4.2 ± 0.8 | 1.9 ± 0.8 | | | |
| OJW | 553 | AH | 0.66 ± 0.2 | 0.29 ± 0.2 | 0.29 | 0.10 | 0.72 | 0.90 ± 0.8 | 0.15 ± 0.8 | 0.46 | 0.03 | 0.78 |
| | | RC | 1.04 ± 0.2 | 0.42 ± 0.2 | | | | 1.27 ± 0.8 | 0.32 ± 0.8 | | | |
| IG | 228 | AH | 6.1 ± 1.0a | 7.8 ± 1.0a | 0.43 | 0.20 | 0.78 | 5.37 ± 1.0 | 10.12 ± 1.0 | 0.66 | <0.01 | 0.57 |
| | | RC | 5.5 ± 1.0b | 6.6 ± 1.0b | | | | 4.3 ± 1.0 | 10.27 ± 1.0 | | | |

^{a,b} Different letters indicate statistically significant difference between the RC and HA breed groups within site and season (*t*-test $P < 0.05$).

^a Vegetation classes for JER (sub-dominant plant species): *Sporobolus flexuosa* (SPFL), *Asistida purpurea* (ARPU), *Pleuraphis mutica* (PLMU), *Yucca elata* (YUEL), *Sporobolus airoides* (SPAI), *Scleropogon brevifolius* (SCBR), *Prosopis glandulosa* (PRGL).

^b Vegetation classes for RET (dominant plant species): Oak-Pine Woodland (OPW), Oak Woodland (OW), Oak-Juniper Woodland (OJW), Intermediate Grassland (IG).

limiting. Recent studies reporting diet selection (Estell et al., this issue) and heat tolerance (Nyamuryekung'e et al., 2021b) of RC vs. AH cows in the Chihuahuan Desert suggest that RC are better able to switch to less palatable forages during the dormant season and likely expend less water than AH for thermoregulation needs during hot summer days. Not surprisingly, breed differences in movement patterns were greatest at JER (we found significant site \times season \times breed interactions for distance traveled and MCP), the harshest of the two sites.

Raramuri Criollo cows allocated less time to grazing (both seasons, both sites) and more time to resting (RET fall) or traveling (JER both seasons, RET spring) than AH counterparts. The lighter weight (and smaller) RC cows may have lower daily dry matter intake requirements which likely freed up time to search dispersed forages, especially at JER, or during times of the year at both sites when less herbaceous biomass was available. Animal body frame and weight (AH > RC) may have impacted the time that cows spent grazing which would be consistent with previous research showing that both of these phenotypic traits are directly related to dry matter intake requirements (Rook et al., 2004). Other factors, in addition to body frame and weight may also be responsible for the breed differences observed. Subsequent studies reported either no differences in time spent grazing by RC and AH cows when forages were dormant or beginning to green up in the spring (Spiegel et al., 2019) or greater time spent grazing by RC vs. AH in both winter and summer (Nyamuryekung'e et al., 2022; Duni et al., this issue). Nonetheless, all studies cited above consistently showed that RC cows allocated significantly more time of their day to travel in search for forages compared to AH counterparts.

A few ecologically significant breed-related differences were observed in the time that cows spent grazing and resting in each vegetation type, particularly during the season when forages were scarce. During the fall at JER, RC cows spent significantly less time than AH grazing and resting in vegetation types with high black grama (*Bouteloua eriopoda*) cover (ARPU vegetation type) when grasses were likely dormant, a pattern that is consistent with subsequent habitat (Spiegel

et al., 2019 and Nyamuryekung'e et al., 2022) and diet selection (Estell et al., this issue) studies conducted in the Chihuahuan Desert. Black grama is considered the most important forage species in the Chihuahuan Desert (Holechek and Herbel, 1982) but has declined considerably over the last century due to a number of management- and environment-related factors (Havstad et al., 2000). Winter grazing of this stoloniferous grass can be detrimental (Bestelmeyer et al., 2013), therefore dormant season differences in grazing of vegetation types where black grama is abundant (RC < AH) could have significant conservation implications for this ecosystem (Spiegel et al., 2019; Nyamuryekung'e et al., 2022). During fall, Raramuri Criollo cows also tended to spend more time than AH counterparts grazing and resting in SPAI, a vegetation type with abundant tobosa grass (*Hilaria mutica*) which is a species that is usually avoided by cattle during dormancy.

At RET, RC cows spent more time grazing in areas with a woodland-grassland mix. It is possible, however, that differences in use of this vegetation class were a consequence of terrain use by each breed. Compared to RC, AH cows grazed lower elevation sites with gentler slopes which support intermediate grasslands vegetation type at this site. Terrain use patterns observed in AH, agree with previous work in which grazing and forage utilization by cattle decreases as terrain slope increases (Bryant, 1982; Pinchak et al., 1991; Bailey et al., 1996). A degree of complementarity was observed in how RC and AH grazed the rangeland pasture at RET. While RC tended to spend more time in higher elevation woodland types (e.g. oak-juniper woodland), AH cattle predominantly grazed lower elevation grasslands. A recent breed comparison study conducted at site with similar vegetation structure and rainfall regime in Argentina suggested a degree of complementarity in landscape use of Argentine Criollo and Angus cows (Herrera Conegliano et al., 2022).

Investigation of animal metabolic and physiological mechanisms driving breed differences in movement, activity, and vegetation use were beyond the scope of this study. It is possible, however, that contrasting acquisition, expenditure, and partitioning of nutrients

(especially energy) driven by breed-specific traits (e.g. body size) could explain much of the observed variation. Cibils et al. (this issue) computed a metric they called 'grazing effort' (a coarse proxy for relative energy expenditure while foraging) by calculating distance traveled per unit of time spent grazing. These authors found that RC and AH cows at both JER and RTE exhibited comparable grazing effort during the season when forages were more abundant (spring at JER and fall at RTE), but that RC appeared to invest more effort in the foraging process than AH during the season when forages were dormant and/or less abundant (fall at JER and spring at RTE). It appears that RC cows are somehow able to allocate more energy to locomotion when forages are scarce, either because they are able to compose more nutritious diets to offset the greater expenditure or, alternatively, because they partition metabolizable energy differently. Given that nutrient partitioning is closely related not only to a cow's activity patterns but, more importantly, to its reproductive success (Mulliniks et al., 2011) understanding nutrient metabolism of RC vs AH cows is, in our view, an essential next step in predicting breed behavior and production outcomes.

5. Conclusions

Significant differences in foraging behavior of heritage and commercial beef cows were observed at two very contrasting rangeland sites included in this study. Raramuri Criollo cattle traveled further and explored larger areas of desert rangeland or grazed on steeper slopes of higher elevation rangeland compared to AH, and differences were more noticeable when forages were dormant or scarce. At both sites, Criollo cattle showed lesser preference for palatable grama grasses than British beef breed counterparts. Overall breed differences in foraging behavior likely reflected the outcome of contrasting selection pressures (natural vs. artificial selection) through time which could have implications for the long-term sustainability of the pastoral systems in the region which are predicted to become increasingly heterogeneous due to the impacts of climate change (Klemm et al., 2020).

Disclaimer

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CRedit authorship contribution statement

O. Roacho Estrada: Funding acquisition, Data curation, Data Acquisition and Curation, Graphics, GIS, Writing – original draft. **F.A. Rodríguez Almeida:** Funding acquisition, Statistical Analyses, Writing – original draft, Writing – review & editing. **S.A. Utsumi:** Data curation, Writing – review & editing. **E.L. Fredrickson:** Conceptualization, Funding acquisition, Supervision, Investigation, Writing – original draft. **G.A. Bezanilla Enríquez:** Conceptualization, Supervision, Investigation, Writing – original draft. **A.F. Cibils:** Writing – review & editing. **R. E. Estell:** Funding acquisition, Writing – review & editing. **A.L. Gonzalez:** Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

We thank two anonymous reviewers for comments that improved an earlier version of this paper. Authors wish to thank all undergraduate and graduate students and staff at New Mexico State University and Universidad Autónoma de Chihuahua as well as technicians at the USDA ARS Jornada Experimental Range that have contributed to the execution of this study. We also wish to acknowledge the collective work and dedication of generations of Tarahumara (Raramuri) communities of the Copper Canyon in Chihuahua, Mexico, who have raised and conserved Criollo cattle herds for close to four centuries, making possible the conservation of this genetic resource.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jaridenv.2023.104943>.

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