



Foraging behavior of Raramuri Criollo vs. Angus cattle grazing California Chaparral and Colorado Plateau shrublands[☆]

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ABSTRACT

Selecting livestock genetics adapted to arid environments, such as Criollo cattle, is one of several strategies recommended for decreasing the vulnerability to climate change of ranching in the southwestern USA. Our objective was to determine whether desirable foraging traits of Criollo cattle previously documented in the Chihuahuan Desert, held true in two of the most climate-vulnerable ecosystems of the Southwest. We conducted a study at Rancho Corta Madera (RCM) in southern California and Dugout Ranch (DR) in southeast Utah. Twenty mature cows, 10 Raramuri Criollo and 10 Red or Black Angus, were monitored with GPS collars during multiple seasons between 2018 and 2021. Geolocation data were used to compute daily distance traveled ($\text{km}\cdot\text{d}^{-1}$), movement velocity ($\text{m}\cdot\text{min}^{-1}$), path sinuosity (SI), time spent grazing, resting, or traveling ($\text{h}\cdot\text{d}^{-1}$), and area of the pasture explored ($\text{ha}\cdot\text{d}^{-1}$) as well as to calculate selection of vegetation cover types (*E*, Ivlev's Electivity Index) by cows of each breed. The effects of breed, season, year, and pasture on each of these metrics were modeled with repeated measures analyses of variance. At both ranches, statistically detectable differences ($P \leq 0.05$) between breeds were observed for most behavior metrics during the dormant season. Conversely, few breed differences were observed during the growing season. Criollo cattle exhibited greater relative preference for a number of shrub dominated vegetation types at both ranches, and similar relative selection of grassland dominated sites compared to Angus counterparts. At both ranches, Criollo cattle exhibited similar or less relative preference for riparian areas vs. Angus counterparts. Breed divergence vs. convergence of foraging behaviors during the dormant vs. growing seasons, previously observed in the Chihuahuan Desert, was documented at both sites. Positive system outcomes associated with foraging traits of Criollo cattle could be expected to occur more broadly across the Southwest.

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1. Introduction

Climate change is expected to increase the vulnerability of pastoral livelihoods worldwide through its projected suppression of forage growth on rangelands of most continents, and its predicted amplification of inter- and intra-annual fluctuations in grazeable herbaceous biomass (Godde et al., 2020). According to the most recent National Climate Assessment for the United States (NCA4, Reidmiller et al., 2018), climates of the southwestern USA are becoming hotter and drier, with more frequent weather extremes and increasingly erratic precipitation patterns. Selecting livestock genetics adapted to foraging in hot arid environments, such as Criollo cattle, is one of several strategies recommended by the NCA4 to decrease vulnerability of desert ranching in the region (Gonzalez et al., 2018). Although a number of recent studies provide strong support for this recommendation (Estell et al., 2022; McIntosh et al., 2021; Nyamuryekung'e et al., 2021; Nyamuryekung'e et al., 2022; Spiegel et al., 2019; Torell et al., 2023 this issue), the geographic scope of this research was limited to a single location in the northern Chihuahuan Desert (Estell, 2021). Whether the more dispersed patterns of herbivory pressure of Criollo cattle documented at this site (hereafter referred to as desirable foraging traits) are true for other southwestern ecosystems is unknown.

Some areas of the southwestern United States, such as eastern Utah and southern California, have suffered a more pronounced increase in temperatures relative to the Chihuahuan Desert (Gonzalez et al., 2018). Megadroughts of unprecedented severity, not documented in the region for 1200 years (Williams et al., 2022), have been especially acute in the Four Corners area (SE Utah, SW Colorado, NE Arizona, and NW New Mexico). Region-wide warming has also triggered an increase in frequency, extent, and severity of wildfires, especially in California, the state with the greatest increase in land area burned each year over the past decade (USEPA, 2022). Not surprisingly, ranchers from these two regions, who are perhaps the most climate-vulnerable in the Southwest, are among the early adopters of desert-adapted beef cattle genetics (Spiegel et al., 2020). Two such ranches, one in southeast Utah and another in southern California, were pioneers in introducing Criollo genetics of the Raramuri biotype into their herds. These were the sites where our research was conducted.

Climate adaptation strategies that enable ranchers to stay on the land are urgently needed, particularly in the most vulnerable areas where impacts of climate change are predicted to be most severe. Preserving southwestern "working rangelands", i.e. extensive landscapes actively managed by ranchers that can support both livestock production and valued natural resources (Huntsinger and Sayre, 2007; Larson et al., 2015), is of pivotal importance to rangeland conservation (Brunson and Huntsinger, 2008; Buckley Biggs, 2022). Ranchers across the region remain in ranching despite low financial returns because of the experiences, lifestyle, and interaction with nature that ranching provides (Gentner and Tanaka, 2002; Huntsinger et al., 2010; Oviedo et al., 2012; Rowe et al., 2001; Smith and Martin, 1972). However, industry challenges now exacerbated by climate change could result in attrition, ranch sales, and the loss of working rangelands (Huntsinger and Hopkins, 1996; Liffmann et al., 2000; Sulak and Huntsinger, 2007) which could have devastating impacts on dryland conservation.

Cattle grazing patterns on rangeland are closely linked with key beef production and environment conservation outcomes (McIntosh et al., 2021; McIntosh et al., 2023 this issue; Sawalhah et al., 2016; Spiegel et al., this issue; Wesley et al., 2012). Our overarching goal was to determine whether desirable foraging traits of Criollo cows, which have been associated with positive system outcomes in the Chihuahuan Desert, held true in other southwestern pastoral ecosystems. Ultimately, we sought to make broader inferences about the suitability of raising Criollo cattle as a climate adaptation strategy for cow-calf operations across the region. Based on patterns previously observed by Spiegel et al. (2019) and Nyamuryekung'e et al. (2022) in the Chihuahuan Desert, we hypothesized that foraging behavior of both breeds would diverge

during times of the year when herbaceous forages were dormant or scarce but would be similar during periods of green-up. Compared to Angus crossbred cows, Raramuri Criollo cattle in the Chihuahuan Desert are better able to adjust their movement and activity patterns to match seasonal forage dynamics (Nyamuryekung'e et al., 2022; Peinetti et al., 2011; Roacho Estrada et al., 2023 this issue; Spiegel et al., 2019). Breed differences in body weight (McIntosh et al., 2020), diet selection (Estell, 2021), mothering style (Nyamuryekung'e et al., 2021a; Nyamuryekung'e et al., 2020) and heat tolerance (Nyamuryekung'e et al., 2021b) are thought to explain this phenomenon. We predicted that Criollo cows would spread out more broadly across the landscape relative to British breed counterparts during periods when vegetation was dormant or brown but that no breed-specific differences would be observed during times of the year when forages were actively growing (green).

2. Materials and methods

2.1. Study sites

Our study was conducted at two commercial ranches, Rancho Corta Madera (RCM) in southern California and Dugout Ranch (DR) in southeastern Utah (Fig. 1). Rancho Corta Madera (32°45'36"N 116°34'12"W), a 2700 ha ranch (~2026 ha deeded and ~740 ha U.S. Forest Service) located in Pine Valley, San Diego County, California, USA, is flanked by the pine forested Laguna mountains to the east and California chaparral dominated landscapes to the west which progressively decline in elevation toward the Pacific Ocean. The ranch is divided into four primary pastures and is owned by a conservation stakeholder group that prioritizes restoration initiatives. Vegetation of RCM includes California annual grassland, high-country chaparral, oak savannas, and, notably, a unique (due to their existence at a relatively low elevation) stand of Jeffrey pine (*Pinus jeffreyi*). Of the total ranch area where cows were monitored, ~20% can be classified as annual and perennial grassland, while the rest is classified as either chaparral or forestland. The climate of Pine Valley is considered warm-summer Mediterranean with an annual mean temperature of 19.4 °C. December is the coldest month with an average temperature of 5 °C while August is the hottest month with an average temperature of 20.6 °C. Occasional snowfall may occur in winter, but is not long lasting. Mean average precipitation is 601 mm, with >68% falling in winter during the months of December, January, February, and March. Over 70% of the soils on the ranch are loamy coarse sand and stony loam of the La Posta and Bancas associations, respectively (USDA-NRCS, 2022).

Low-lying grasslands are composed of common grasses including Thurber's needlegrass (*Achnatherum thurberianum*), brome (*Bromus carinatus*), soft chess (*Bromus hordeaceus*), red brome (*Bromus rubens*), California oatgrass (*Danthonia californica*), California buckwheat (*Eriogonum fasciculatum*), purple needlegrass (*Nasella pulchra*), bluegrass (*Poa atropurorea*), desert needlegrass (*Stipa speciosa*), foxtail fescue (*Vulpia myuros* var. *hirsuta*) and several native annual grasses (USDA-NRCS, 2022).

Upland chaparral shrublands are composed of perennial grasses and common shrubs including chamise (*Adenostoma fasciculatum*), manzanita (*Arctostaphylos* spp.), big sagebrush (*Artemisia tridentata*), ceanothus (*Ceanothus* spp), goldenbush (*Isocoma* spp), desert almond (*Prunus fasciculata*), antelope bitterbrush (*Purshia tridentata*), desert bitterbrush (*Purshia* sp.), coastal sage scrub oak (*Quercus dumosa*), and numerous other oaks (*Quercus* spp.) (USDA-NRCS, 2022).

Forested areas on the ranch are primarily composed of trees including Jeffrey pine, redshank (*Adenostoma sparsifolium*), and single-leaf pinyon (*Pinus monophylla*). Stork's bill (*Erodium cicutarium*) and staghorn clubmoss (*Lycopodium clavatum*) are ubiquitous forbs across the entire ranch area.

The Dugout Ranch (DR; 38° 4' 13" N, 109° 33' 54" W), San Juan County, UT, USA, is located on the Colorado Plateau (Fig. 1) southeast of

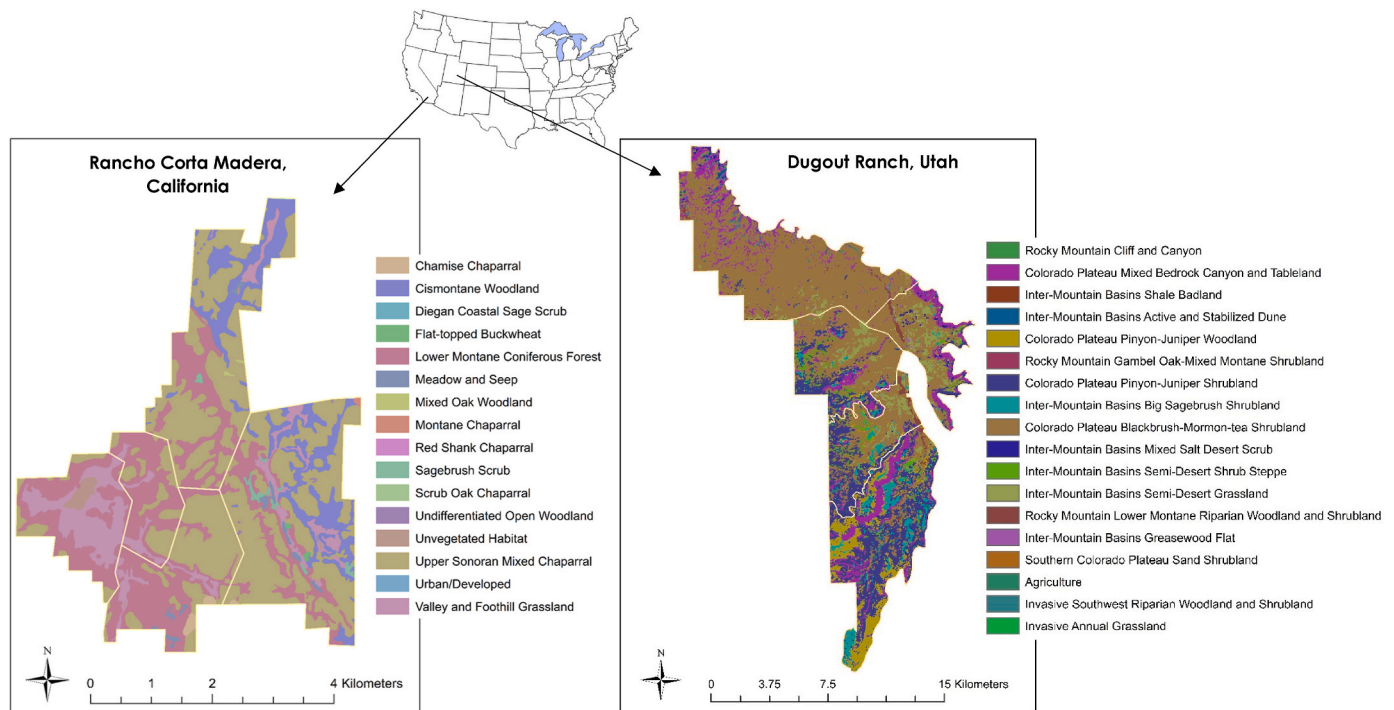


Fig. 1. Maps showing ranch perimeter and pasture boundaries, approximate geographic location, and vegetation cover for Rancho Corta Madera (RCM, Forest Service Allotment not shown) in southern California and Dugout Ranch (DR) in southeast Utah (only winter pastures shown for DR). Vegetation maps were developed by the San Diego County (RCM) and the Southwest Regional Gap Analysis Project (DR). See methods section for further details.

the confluence of the Green and Colorado Rivers and is surrounded by steep sandstone cliffs with cottonwood creek beds and shrub-grass covered buttes. The ranch is owned and managed by the Nature Conservancy and is home of the Canyonlands Research Center (canyonlandsresearchcenter.org). It comprises 2107 ha of private land and 135,582 ha of Bureau of Land Management (BLM) and U.S. Forest Service (USFS) grazing allotments (Fig. 1, USFS allotment not shown). The Bureau of Land Management allotment included the five winter grazing desert pastures used in this study and shown in Fig. 1 which ranged in area from 2534 ha (Creek Pasture) to 7480 ha (Park Pasture). The biophysical characteristics of the DR study pastures include elevations ranging from 1125 to 2221 m and a cool desert climate with a long term mean annual precipitation of 215 mm, with high interannual variability and increasing temperatures over the previous 50 years (Finger-Higgins et al., 2022). Frontal storms comprise 65% of annual precipitation and occur during winter and spring while the remaining precipitation generally falls during the summer as monsoonal thunderstorms (Hereford and Webb, 1992). The region has a mean annual temperature of 13.3 °C; January is the coldest month with an average temperature of -1.8 °C while July is the hottest month with an average temperature of 26.0 °C. Growing season is generally from April 1st to October 31st (Western Regional Climate Center, 2022).

Soils of the DR study pastures were predominantly fine loamy sands, with grasslands and grass-shrub mixes on deeper soils, shrublands and savannas on shallow soil settings, with biological soil crusts often covering exposed soils between vascular plants (Duniway et al., 2022). Study pastures ranged in area from 2534 ha to 7480 ha (Fig. 1). Common annual and perennial C3 and C4 species included: thick-sepal cat's-eye (*Cryptantha crassisejala*), indian ricegrass (*Achnatherum hymenoides*), Thurber's needlegrass (*Achnatherum thurberianum*), alkali sacaton (*Sporobolus airoides*), sand dropseed (*Sporobolus cryptandrus*), spike dropseed (*Sporobolus contractus*), mesa dropseed (*Sporobolus flexuosus*), blue grama (*Bouteloua gracilis*), inland saltgrass (*Distichlis spicata*), needle and thread (*Hesperostipa comata*), prairie junegrass (*Koeleria macrantha*), saline wildrye (*Leymus salinus*), Squirreltail (*Elymus*

elymoides), western wheatgrass (*Pascopyrum smithii*), muttongrass (*Poa fendleriana*), bluegrass (*Poa* sp.), sandberg bluegrass (*Poa secunda*), and James' galleta (*Pleurapis jamesii*) (USDA-NRCS, 2022).

Common woody plants, forbs and cacti include: prickly Russian thistle (*Salsola tragus*), barbwire Russian thistle (*Salsola paulsenii*), Bigelow sagebrush (*Artemisia bigelovii*), black sagebrush (*Artemisia nova*), Wyoming big sagebrush (*Artemisia tridentata*), fourwing saltbush (*Atriplex canescens*), shadscale saltbush (*Atriplex confertifolia*), true mountain mahogany (*Cercocarpus montanus*), green rabbitbrush (*Eriogonum microthecum*), slender snake-weed (*Gutierrezia sarothrae*), winterfat (*Krascheninnikovia lanata*), rabbitbrush (*Chrysothamnus* sp.), Mexican cliffrose (*Purshia mexicana*), greasewood (*Sarcobatus* sp.), globemallow (*Sphaeralcea ambigua*), pricklypear (*Opuntia* sp.), smallflower tamarisk (*Tamarix parviflora*), Fremont cottonwood (*Populus fremontii*), sandbar willow (*Salix sessilifolia*), roundleaf buffaloberry (*Shepherdia rotundifolia*), blackbrush (*Coleogyne ramosissima*), and Mormon tea (*Ephedra viridis*) (USDA-NRCS, 2022).

2.2. Vegetation mapping

A land cover map developed by the San Diego Association of Governments based on the Holland (1986) hierarchical classification of California's vegetation was used for RCM (Fig. 1, SANDAG, 2013; Sproul et al., 2011). The dataset was projected to WGS 1984 UTM Zone 11 North in ArcGIS 10 (ESRI, Redlands, CA) and clipped to the outline of the ranch boundary. The RCM included 15 cover types and their corresponding codes: Urban/Development (12,000); Unvegetated Habitat (13,000); Valley and Foothill Grassland (42,000); Meadow and Seep (45,000); Cismontane Woodland (71,000); Mixed Oak Woodland (77,000); Undifferentiated Open Woodland (78,000); Lower Montane Coniferous Forest (84,000); with the sub-classification of the Scrub and Chaparral (30,000) including Diegan Coastal Sage Scrub (32,500), Sagebrush Scrub (35,200), Upper Sonoran Mixed Chaparral (37,100), Chamise Chaparral (37,200), Red Shank Chaparral (37,300), Montane Chaparral

(37,500) and Flat-topped Buckwheat (37K00) (Fig. 1). The vegetation map was compared with satellite imagery data, which indicated well-delineated land cover type boundaries. A detailed description of vegetation types is provided by Sproul et al. (2011).

The vegetation map for DR was derived from the land cover layer of the Southwest Regional Gap Analysis Project (Lowry et al., 2005, Fig. 1). This layer was originally developed using 30 m resolution Landsat ETM+ images and a digital elevation model (DEM) of the region. Nature-Serve's Ecological System concept was the basis for the landcover classes (Lowry et al., 2005). Winter pastures at DR included thirteen vegetation cover classes including Colorado Plateau Mixed Bedrock Canyon and Tableland, Inter-Mountain Basins Active and Stabilized Dune, Colorado Plateau Pinyon-Juniper Woodland, Rocky Mountain Gambel Oak-Mixed Montane Shrubland, Colorado Plateau Pinyon-Juniper Shrubland, Inter-Mountain Basins Big Sagebrush Shrubland, Colorado Plateau Blackbrush-Mormon-tea Shrubland, Inter-Mountain Basins Mixed Salt Desert Scrub, Inter-Mountain Basins Semi-Desert Shrub Steppe, Inter-Mountain Basins Semi-Desert Grassland, Rocky Mountain Lower Montane Riparian Woodland and Shrubland, Inter-Mountain Basins Greasewood Flat, and Invasive Southwest Riparian Woodland and Shrubland. For a detailed description of cover types see Lowry et al. (2005).

2.3. Weather and NDVI data

Weather records for RCM were retrieved from a National Oceanic and Atmospheric Administration (NOAA) weather station located in the town of Alpine (32° 50' 43.692" N, 116° 42' 22.392" W), approximately 15.4 km northwest of the RCM headquarters (32° 45' 47.376" N, 116° 34' 25.3308" W). At DR, we used weather data recorded on site at the Monticello-Indian Creek weather station (38° 8' 24.72"N, 109° 36' 59.4" W) which were retrieved from the Utah Climate Center (2022) website.

To evaluate greenness in the study pastures, Normalized Difference Vegetation Index (NDVI) of Moderate Resolution Imaging Spectroradiometer (MODIS) Terra Vegetation Indices 16-Day L3 Global 250m Grid (MOD13Q1) were acquired from the Level-1 and Atmosphere Archive & Distribution System (LAADS) Distributed Active Archive Center (DAAC) of Goddard Space Flight Center. Using a boundary shapefile that covers the study pastures, MOD13Q1 images between 2018 and 2021 were extracted and processed using online services provided by LAADS-DAAC. Image post processing steps including image mosaicking, reprojection (i.e., from sinusoidal to geographic coordinate system), and reformatting were conducted using the online services. The coordinates of each pixel (i.e., centroid) in the study pastures were generated and used to extract NDVI values of the study period using R (R Core Team, 2021). Monthly NDVI of each pixel was calculated by averaging bimonthly NDVI values of the pixels in the pastures. Mean monthly NDVI of the pastures was obtained by averaging monthly NDVI of each pixel that are found in each pasture during 2018–2021.

2.4. Animal handling and monitoring

All animal handling protocols for this study were approved by the New Mexico State University Institutional Animal Care and Use Committee (IACUC; Protocol #2019–012). Black Angus (BA) cows used at RCM had been bred and raised at the ranch from several successive generations beginning in the 1990's and had small amounts of Brahman and Longhorn influence. Red Angus (RA) cows used at DR were part of the ranch herd that has been selected for over 50 years to fit the ranch environment and management system. Raramuri Criollo cattle were provided to RCM and DR by the USDA ARS Jornada Experimental Range in 2017 and 2018, respectively. The Jornada RC herd consists of cattle originally introduced from the Copper Canyon of Chihuahua, Mexico (Anderson et al., 2015; Estell, 2021) and have been described in detail by McIntosh et al. (2020). Since arriving at both ranches, RC cattle have grazed jointly with either the BA (at RCM) or RA (at DR) herd. All

collared cows in our study were managed as part of the RCM or DR mother cow herd throughout all trials. Therefore, RC cows co-grazed the same pastures with RA or BA as in previous studies reported by Herrera Conegliano et al., 2022 (this issue), Peinetti et al. (2011), and Roacho Estrada et al., 2023 (this issue). Throughout the study, cows had ad libitum access to fresh water from drinkers, streams, ponds, and dirt tanks. At RCM, cattle grazed the deeded land in winter through early fall and were moved on to an adjacent U.S. Forest Service allotment in late fall. A small and incomplete cattle monitoring data set was available for USFS allotment grazing and therefore those data were excluded from analyses. Cattle at RCM were moved from the west to the east pastures of the ranch seasonally and were gathered annually for vaccination, branding, and weaning (Table S1, Suppl. Mat). At DR, cattle were moved on horseback through the large winter pastures (see Fig. 1 and Table S1, Suppl. Mat.) using low stress handling techniques (as in Grandin, 2014) and following a grazing schedule as shown in Table S1 (Suppl. Mat). Mineral and salt were provided to the herd in all pastures. At both ranches, calving occurred in March and April of each study year, except for the first year of the study at DR when some of the RC cows calved earlier (January–February).

At RCM, Lotek 3300 LR-GPS collars (Lotek Wireless, New Market, ON, Canada) were fitted on 20 mature (>3y) BA and RC mother cows (10 per breed) weighing approximately 600 kg and 480 kg, respectively. Collars stored data onboard, had a battery life of approximately 45 days, and were equipped with two axis accelerometers, temperature sensors, and radio beacons. GPS collars were programmed to record data at 10-min intervals following protocols used in previous studies (Nyamur-yekung'e et al., 2022; Peinetti et al., 2011; Spiegel et al., 2019). Collar deployment coincided with herd gathering schedules and occurred in different seasons throughout the three years of the study (see below). GPS data were systematically checked for errors; points with dilution of precision (DOP) greater than 11 were removed following Langley (1999). GPS points that were outside of the study pastures were also removed from our analyses. In fall 2019 (Sept–Oct) the timestamp on GPS collars malfunctioned, precluding the use of these data for movement and activity (but not habitat use) analyses. A few collars typically malfunctioned during each sampling date, however data from no less than 4 cows per breed were obtained from each deployment (Table S2 Suppl. Mat.).

At DR, 20 mature (>3y) RA and RC mother cows (10 per breed), weighing approximately 544 kg and 453 kg, respectively, were fitted with Lotek LITETRACK LR-GPS collars (Lotek Wireless, New Market, ON, Canada). Collars stored data onboard and had a battery life of approximately 6 months. Collars were equipped with three axis accelerometers, temperature sensors, proximity loggers, and radio beacons and were also programmed to record data at 10-min intervals. The rate of collar failure was very high during our first deployment (Table S2, Suppl. Mat.) and tended to decrease as the study progressed. Collars at this site were deployed in late October and were recovered for data download in early May of each of the three years of the study. GPS data quality control protocols were the same as those described above for RCM.

All GPS data were projected and mapped using NAD 1983 UTM Zone 11N or 12 N for RCM and DR, respectively, in ArcGIS desktop version 10.6 (ESRI, Redlands, CA). The GIS layers used for analysis included RCM and DR boundaries (fence lines and natural boundaries), livestock drinkers and streams, and respective land cover types described above. Animal movement and activity metrics were calculated using GRAZEACT, a JAVA software described by Gong et al. (2020) which was used to calculate area explored ($\text{ha} \cdot \text{d}^{-1}$), sinuosity index (0 = most sinuous; 1 = straight path), and distance traveled ($\text{km} \cdot \text{d}^{-1}$) for individual collared animals. GRAZEACT uses minimum convex polygon (MCP) to calculate area explored, the Batschelet (1981) straightness index to calculate path sinuosity and computes distance traveled and movement velocity using the Pythagorean Theorem to calculate distance between consecutive GPS fix locations. GPS points were also classified into

activity categories using velocity thresholds following Nyamuryekung et al. (2020). Points were classified as either resting ($<2.34 \text{ m}\cdot\text{min}^{-1}$), grazing ($2.34\text{--}25 \text{ m}\cdot\text{min}^{-1}$), or traveling ($>25 \text{ m}\cdot\text{min}^{-1}$). Classified points were used to compute daily time spent resting, grazing, and traveling by collared cows. Ivlev's selectivity index (E , Jacobs, 1974) was calculated to determine preference ($E > 0$) or avoidance ($E < 0$) for vegetation cover types within each pasture. Electivity is calculated as E

$= (r - p)/(r + p)$ where r is the proportion of time spent by a given cow in a given cover type, and p is the proportion of the pasture covered by that land cover type (See Figs. 1S and 2S, Suppl. Mat.). Ivlev's E was used to rank relative selection of vegetation types by each breed within each grazing pasture at both sites following an approach proposed by Lechowicz (1982).

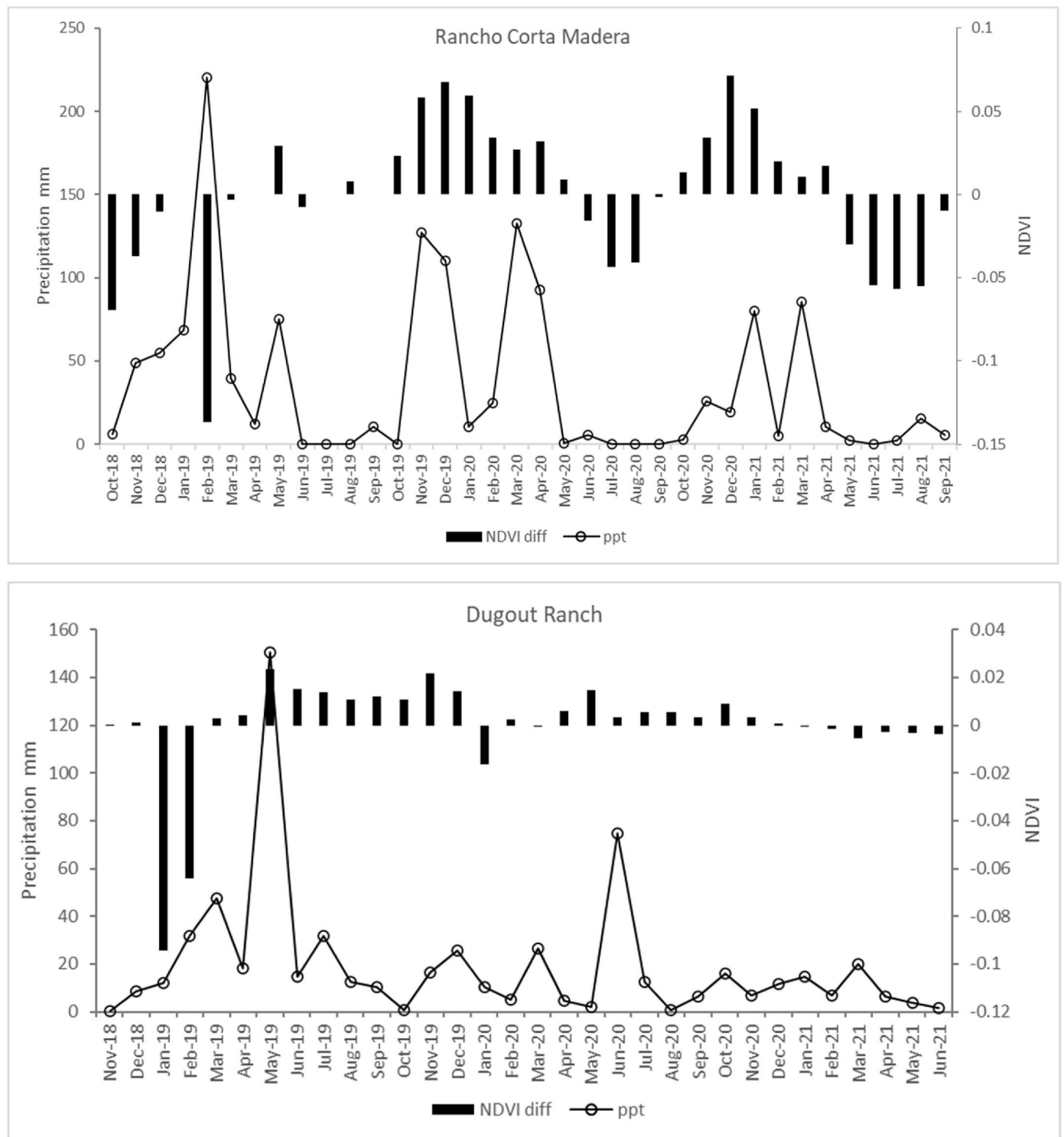


Fig. 2. Monthly precipitation and monthly MODIS-derived NDVI values expressed as deviations from the study period (2018–2021) mean for Rancho Corta Madera (RCM, top) and Dugout Ranch (bottom). Weather records for RCM were retrieved from a NOAA weather station located in Alpine, CA whereas DR weather records were collected on site and were available through the Utah Climate Center. See methods section for further details.

2.5. Statistical analyses

Movement and Activity: Animal GPS monitoring schedules and seasonal vegetation dynamics were different at RCM and DR, therefore data from each site were analyzed separately. For RCM, data were partitioned into seasons representing winter (Dec.–Feb.), spring (Mar.–Apr.), summer (Jul.–Aug.), and fall (Sep.–Oct.). Individual animal-derived variables were averaged weekly using the MEANS procedure in SAS 9.3 to account for an unequal number of sampling days within weeks. A repeated measures analysis of variance was used to model the effects of breed (RC vs. BA), season, and their interaction on patterns of movement (24h and daytime distance traveled, movement velocity, path sinuosity) activity (time spent grazing, resting, or traveling) and area explored (MCP). We used the MIXED procedure in SAS 9.4 (SAS Institute, Cary, NC) to conduct all analyses. Kenward–Roger degrees of freedom was used to adjust the standard errors and denominator degrees of freedom for all tests. Data were modeled using a first-order autoregressive covariance structure AR (1). Least squares means, standard errors, and two-tailed P-values were determined for each response variable. A *contrast* statement was added for each variable, testing the effect of breed within a season. For all analyses, statistical significance was declared at $P < 0.05$.

At DR a repeated measures analysis of variance was used to model the effects of breed (RA vs. RC), year (2018, 2019–20, or 2020–21), and their interaction on patterns of movement (distance traveled, movement velocity, path sinuosity), activity (time spent grazing, resting, or traveling), and area explored (MCP) by cows in late fall (Nov.–Dec.), winter (Jan.–Feb.), and early spring (Mar.–Apr.). Each season was analyzed separately. We used the MIXED procedure in SAS 9.4 (SAS Institute, Cary, NC) to conduct all analyses. Kenward–Roger degrees of freedom were used to adjust the standard errors and denominator degrees of freedom for all tests. Data were modeled using a first order autoregressive covariance structure AR (1). For all analyses, statistical significance was again declared at $P < 0.05$.

Vegetation cover selection: Vegetation selection was analyzed calculating Ivlev's electivity index for each mapped vegetation cover type and cow within each pasture. At RCM, the analysis filtered data to only include cows with three or more complete days' worth of GPS data in a given pasture. To avoid potential statistical biases associated with the use of habitat selection indices such as Ivlev's E (Jacobs 1974), we determined relative selection of vegetation cover types by each breed in a given pasture by placing their E values in rank order and then comparing cover type E rankings of each breed as suggested by Lechowicz (1982). The ranking consisted of sorting electivity indices from greatest (most highly selected, $E > 0$, ranked #1) to smallest (least selected, $E < 0$, ranked last) to conduct a qualitative comparison of each breed's relative selection of vegetation types within a pasture. This approach allowed us to rely less on the absolute value of E by focusing instead on the relative placement of a given cover type's E in relation to all other cover types available to each breed in a given pasture. We viewed this as the most parsimonious method of analyzing vegetation cover selection patterns.

3. Results and discussion

3.1. Rainfall and greenness dynamics

Precipitation at RCM was below the long-term average (601 mm) in 2018 (287 mm), 2020 (314 mm), and 2021 (362 mm), but was slightly above average in 2019 (663 mm). Throughout the study period, most of the precipitation at this site occurred in winter and early spring (Fig. 2). Analysis of MODIS-derived 16d NDVI of the entire ranch confirmed that 2019 was the most favorable year of the study (Fig. 2). Vegetation greenness tended to peak in winter and early spring, coinciding with the region's mild Mediterranean winters, and to decline during the dry summer months. A strong negative NDVI deviation observed in February

2019 (Fig. 2) was associated with the only large snowfall event that occurred during the study period.

Precipitation for the water year (Oct–Sept) at the DR was well above long term average (215 mm) in 2018–19 (410 mm) mostly due to an extremely wet month of May and below average in the 2019–20 and 2020–21 water years (both ~ 185 mm, Fig. 2). The last water year of the study captured a regional drought event, with $>95\%$ of San Juan County, UT in Extreme drought from Dec. 2020 through early Feb. 2021 (US Drought Monitor, <https://droughtmonitor.unl.edu/>). The MODIS-derived 16d NDVI values of the DR study area reflect these weather patterns suggesting that 2019 was the most and 2021 the least favorable year of the study (Fig. 2). The greatest NDVI value in most pastures occurred in spring 2019 and, overall, greenness tended to peak in spring and fall (Fig. 2). Negative NDVI deviations observed in Jan–Feb 2019 and in January 2020 were again associated with winter snowfall events. No clear relationships between NDVI and cattle foraging patterns, such as those reported by Spiegel et al. (2019) and Browning et al. (2018), were detected at either RCM or DR, likely due to the dominance of non-forage woody vegetation at both sites.

3.2. Animal movement and activity

At RCM, we retrieved data from 4 to 10 cows of each breed (Table S2, Suppl. Mat.) in each monitoring period. In winter and spring, the seasons with greatest rainfall and greenness (but see below), RC and BA cows traveled similar distances daily, moved at similar velocities along paths of comparable sinuosity, and allocated similar time to graze, rest, and travel each day (Fig. 3). Winter, however, was the only season in which RC cows covered a larger area of the pasture compared to BA counterparts (Fig. 3), which was counter to our expectations. Other studies reported no breed differences in daily area explored during the green-growing season (Nyamuryekung'e et al., 2022; Roacho Estrada et al., 2023 this issue, Spiegel et al., 2019) or, in the case of Argentine Criollo cattle, Herrera Conegliano et al., 2022 (this issue) reported that in summer (when forages were green) Angus cows explored larger areas of the study pasture compared to Criollo counterparts. In breed comparison studies conducted elsewhere (including the DR study reported here), cows were typically nursing a calf when forages began to green up; however, cows at RCM were dry during the earlier part of the green season (winter, in this case). Further multi-site comparisons would be needed to tease apart the relative influence of a cow's physiological stage (nursing/lactating vs. dry) vs. forage phenology (green vs. brown) on grazing behavior divergence vs. convergence of Criollo and commercial beef cows on rangeland.

Interestingly, at RCM, a snow storm occurred in February 2019 (note NDVI nadir shown in Fig. 2) during which hay was supplied to the herd. We hypothesize that RC cows may have ranged out further from supplement feeding sites during the storm, compared to their BA counterparts who were likely more accustomed to relying on winter emergency feeding. Research assessing RC behavior in relation to extreme weather has naturally focused on their ability to withstand desert heat (Nyamuryekung'e et al., 2021) yet further investigation into RC cattle's behavior during extreme cold spells is needed. The pattern observed at RCM, supports anecdotal accounts of RC cows' behavior during winter snow storms on rangelands of South Dakota (Alfredo Gonzalez, pers. comm.). Supplemental feeding during winter, a common practice on western US ranches, can modify rangeland use patterns of beef cattle (Holechek et al., 2011). Countless experiments have addressed different aspects of this issue (e.g. Cibils et al., 2008; Krysl and Hess, 1993; Rouda et al., 1990; Schauer et al., 2005) but research investigating the influence of winter feeding on spatial distribution patterns of commercial beef breeds vs. Criollo cows, which typically require less supplementation, is lacking.

At RCM, during summer and fall, the seasons with close to no precipitation and a notable decline in vegetation greenness (Fig. 2), RC cattle traveled significantly longer distances, exhibited greater

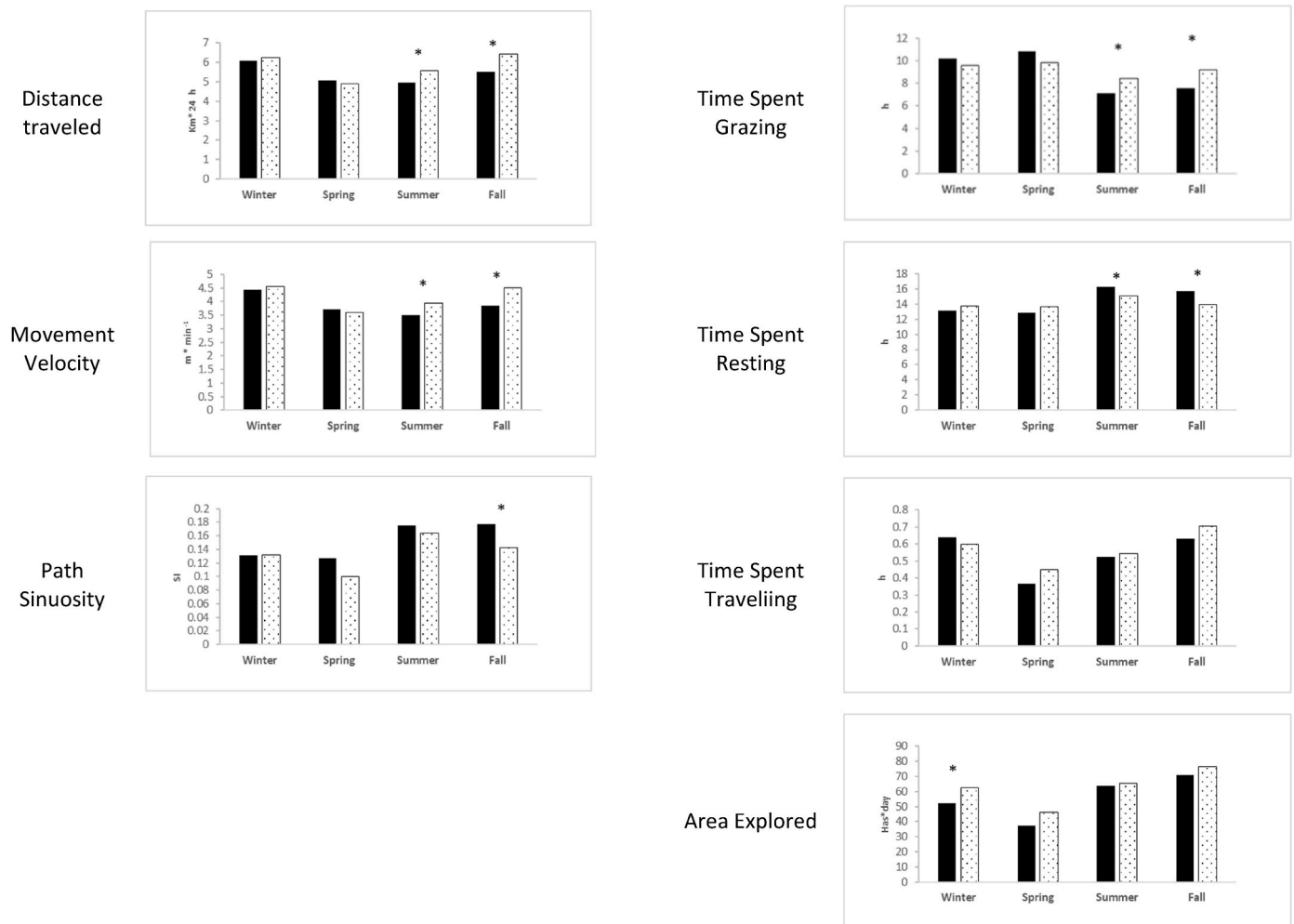


Fig. 3. Movement and activity patterns, and daily area explored by Black Angus (black bars) and Raramuri Criollo (dotted bars) cows tracked with GPS collars at Rancho Corta Madera in winter 2018–19 (Dec 2018–Jan 2019), spring 2019 (Mar–Apr), summers 2020 and 2021 (Jul–Aug), and fall 2021 (Sep–Oct). Asterisks indicate statistically different means at $P \leq 0.05$.

movement velocities, followed more sinuous movement paths (especially in fall), and allocated more time to graze and less time to rest relative to their BA counterparts (Fig. 3). Both breeds spent a similar number of hours traveling and explored similar areas of the pasture each day (Fig. 3). Both the ratio of distance traveled to area explored (data not shown) as well as the path sinuosity index, suggest that during the drier season (forage dry down) forage search patterns of RC cows at RCM differed significantly from that of their BA counterparts (Fig. 3). More concentrated search for forages has been shown to result in greater path sinuosity in both bison (Fortin, 2003) and cattle (Russell et al., 2012). Nonetheless, because the straightness index we used is sensitive to the physical structure (e.g., woody plants) of the foraging environment (Benhamou, 2004), we speculate that increased time spent by RC vs. BA navigating in shrublands of the East pasture (see below) was more likely the cause of sinuosity differences between breeds during fall.

At DR, the majority of GPS collars malfunctioned in the first year of the study (2018–19), therefore we were only able to collect animal movement data in late fall that year. In subsequent years (2019–20 and 2020–21), we retrieved data from two to seven cows of each breed covering the entire six months (three seasons) of yearly monitoring (Table S2, Suppl. Mat). In late fall (forage brown-down), RC cows traveled significantly further at greater movement velocity than RA counterparts in the second and third year of the study (Fig. 4) perhaps reflecting a tendency to select more dispersed forage patches. In 2018, however, cows of both breeds traveled similar daily distances at similar

velocities (Fig. 4). RC cows were brought to DR from the USDA ARS Jornada Experimental Range shortly before the study began and were likely still adapting to the new landscapes and forage species as well as their new social environment in 2018. Still, regardless of adaptation to the new environment, RC cattle consistently followed more sinuous foraging travel paths than RA counterparts in late fall during the first and subsequent years of the study (Fig. 4). RC cows tended to spend more time foraging in shrub-dominated vegetation types (see below) relative to their RA counterparts; therefore, differences in sinuosity were likely driven by the physical structure of the vegetation as in RCM (see above). Breed differences in daily time allocated to graze in this season varied across years of the study. In general, RC cows spent more time grazing and less time resting than their RA peers who tended to graze fewer hours as the study progressed, a trend that caused breed differences to increase with time (Fig. 5). Similar, but inverse, trends were observed in daily time allocated to rest by cows of each breed (Fig. 5). Hypothesized differences in digestibility of forages selected by each breed ($RC > RA$) and/or possible differences in rumen volume ($RC < RA$) may have allowed RC cows to spend more time grazing and less time ruminating (\sim time allocated to rest) compared to RA counterparts. In late fall, RC cows spent more hours traveling compared to their RA counterparts, particularly in the second and third year of the study (Fig. 5). Daily area explored, varied across the three late fall seasons (Fig. 5); overall, MCP of RA cows decreased as the study progressed whereas no year-to-year MCP differences were observed in Criollo

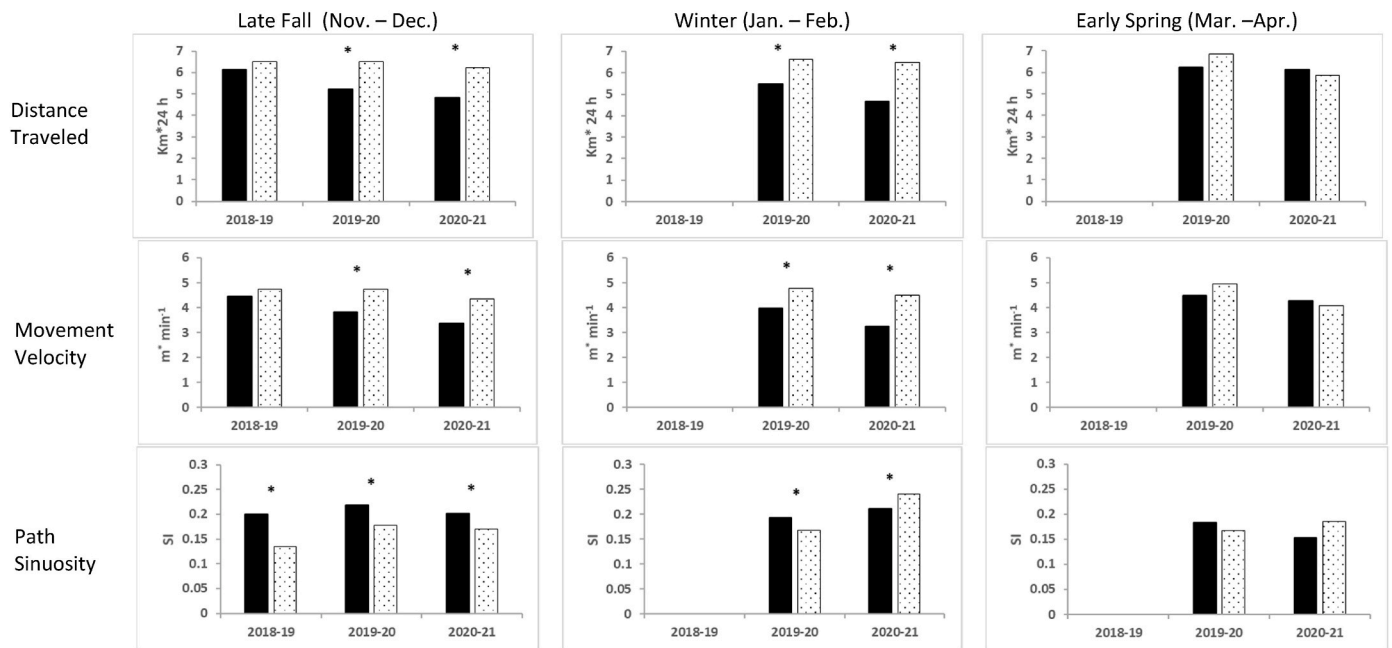


Fig. 4. Movement patterns of Red Angus (black bars) and Raramuri Criollo (dotted bars) cows tracked with GPS collars at the Dugout Ranch in late fall, winter, and early spring of 2018, 2019–20, and 2020–21. Asterisks indicate statistically different means at $P \leq 0.05$.

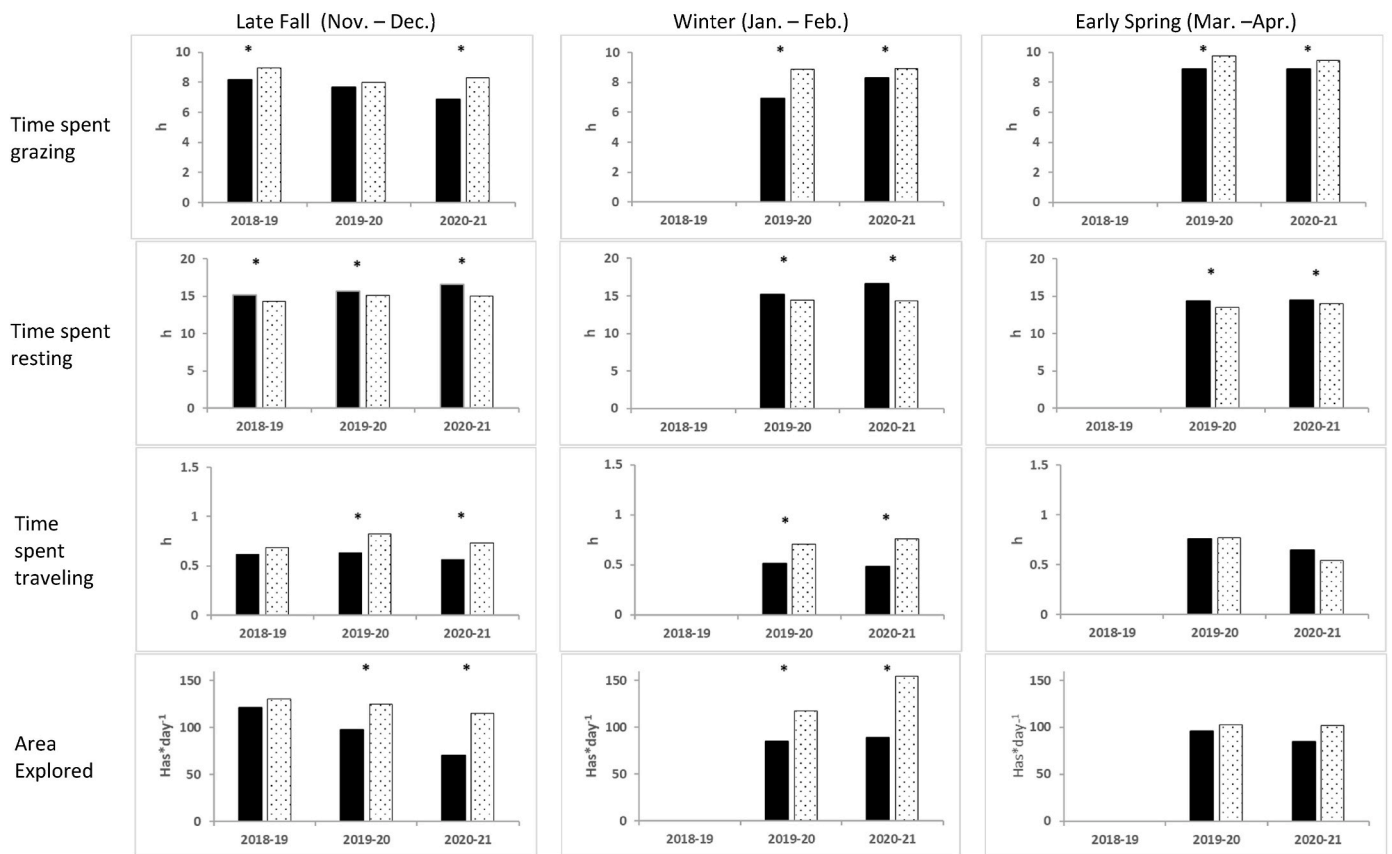


Fig. 5. Activity patterns and area explored by Red Angus (black bars) and Raramuri Criollo (dotted bars) cows tracked with GPS collars at the Dugout Ranch in late fall, winter, and early spring of 2018, 2019–20, and 2020–21. Asterisks indicate statistically different means at $P \leq 0.05$.

counterparts (Fig. 5). Compared to RA peers, RC cows tended to explore larger areas of grazing pastures in late fall; however, breed differences were not statistically detectable in the first year of the study (Fig. 5). Breed MCP differences in late fall increased as the study progressed due

to a tendency of RA cows to explore progressively smaller areas of grazing pastures (Fig. 5).

Similar to what had occurred in late fall at DR, in winter RC cattle walked further at greater velocity rates than RA counterparts (Fig. 4).

Breed differences in path sinuosity, however, varied between years; RC cows followed significantly more sinuous foraging travel paths than their Red Angus peers in winter of 2019–20, whereas the opposite occurred in the following year (Fig. 4). Differences in vegetation structure of pastures grazed during each winter (Park and Creek pastures in 2020 and Davis and Corral Pocket pastures in 2021) could explain this result. Strong selection by RC cows of a shrub cover type (greater path sinuosity) avoided by RA cows which was only available in Park pasture and greater RC avoidance of riparian woodlands in Davis and Corral Pocket, which were weakly avoided or preferred by RA cows, may have been responsible for the observed pattern switching (see Table 2 and below). During winters, RC cows spent overall more time grazing, less time resting, and more time traveling each day compared to RA counterparts (Fig. 5), but the magnitude of differences between breeds varied from one year to the next (Fig. 5). RC cows consistently explored larger areas of the grazing pastures each day, relative to their RA counterparts, but breed difference was largest in the winter of 2021 (Fig. 5) which followed a growing season with very modest vegetation green up (Fig. 2).

Social interactions among RC and RA cows could have been responsible for the trend toward progressive divergence of foraging behavior metrics of each breed through time. Behavior variables of RC cows were fairly consistent through time whereas RA appeared to gradually return to a presumed baseline as the study progressed (Figs. 4 and 5). We speculate that introducing of RC cows into the herd at DR could have altered foraging patterns of RA cows initially, but that social influences likely decreased through time. Nyamuryekung'e et al. (2022) reported that herd cohesion was greater in British crossbred cows relative to RC cattle grazing separately in the Chihuahuan Desert, but social interactions between RC and commercial beef cows co-grazing common pastures has not been investigated. Most studies comparing grazing behavior of Criollo vs. British beef cows where both breeds grazed jointly, assumed no social influences of one breed on the other (Herrera Conegliano et al., 2022 this issue; Peinetti et al., 2011; Roacho Estrada et al., 2023 this issue). Although breed differences in foraging behavior have been documented regardless of whether RC and British beef cows graze jointly (references above) or separately (Nyamuryekung'e et al., 2022; Spiegel et al., 2019), our results suggest that social interactions could trigger transient changes in foraging behavior of one or both breeds. Given what is known about the role of horns in establishing social dominance in cattle herds (Bouissou, 1972) and based on what we observed at this site we suspect that Criollo cattle likely alter the behavior of hornless herd peers, albeit transiently, but a controlled ethology experiment is needed to test this hypothesis and assess its ecological significance.

In early Spring, the season with increasing NDVI (though not in 2021), no statistically detectable differences between breeds were observed for any of the four movement metrics analyzed at DR (Fig. 4). However, RC cows spent significantly more time grazing and less time resting each day, compared to their RA peers (Fig. 5). Differences in rumen volume and/or the quality of diets selected by each breed (mentioned above) may have been responsible for this result. No breed differences in time allocated to traveling or daily area explored were observed in spring of either year of the study (Fig. 5).

Convergence of foraging behavior patterns of RC vs. improved British beef cattle during the season with greater availability of green forages and divergence during dormant seasons, observed at both RCM and DR, agrees with what has been reported in studies conducted in the Chihuahuan Desert (Nyamuryekung'e et al., 2022; Peinetti et al., 2011; Roacho Estrada et al., 2023 this issue; Spiegel et al., 2019) as well as in the Sierra Madre foothills of Chihuahua, Mexico (Roacho Estrada et al., 2023 this issue). Convergence/divergence of foraging behaviors of RC vs. improved beef breeds has now been carefully documented in summer vs. winter (Nyamuryekung'e et al., 2022; Spiegel et al., 2019) or spring vs. fall (Peinetti et al., 2011; Roacho Estrada et al., 2023 this issue) in the Chihuahuan Desert, fall vs. spring in the Sierra Madre foothills (Roacho

Estrada et al., 2023 this issue), winter vs. summer-fall in the Mediterranean environment of RCM and spring vs. late fall-winter in the Colorado Plateau rangelands of DR. The fact that this pattern has been observed in different seasons in each of these four ecosystems, and in comparisons involving RC vs. several improved British beef cattle breeds suggests that earlier reports of behavior differences between breeds (Peinetti et al., 2011; Roacho Estrada et al., 2023 this issue) could be extrapolated with caution across the region. It is important to note, however, that such differences could be constrained by management and ranch infrastructure. The absence of dry season divergence of daily area explored by RC and BA cows at RCM, which was not anticipated, may have reflected the relatively small size of grazing pastures at the ranch relative to other study sites (~350–600 ha vs. 1200 ha or more at other desert ranches). The conservation value of foraging behaviors observed in RC could vary across the region as well. Whether observed behavior patterns of RC at DR are compatible with protection of fragile biological soil crusts (Concostrina-Zubiri et al., 2014; Root et al., 2020), a conservation priority for rangelands of the Colorado Plateau, has yet to be determined. Further research is needed addressing seasonal divergence of foraging patterns in relation to varying levels of biological soil crust vulnerability to disturbance that occur throughout the year.

3.3. Vegetation cover type selection

At RCM, meadows and grasslands were the first or second most selected vegetation types by both breeds (Table 1). However, in North pasture, BA cows showed higher preference for meadows than RC counterparts in both absolute (E : 0.95 vs. 0.50) and relative (rank # 1 vs. 2) terms. The opposite was true of breed selection patterns of grasslands in that pasture (Table 1). The largest difference in relative selection of a given vegetation type by each breed was observed in a woodland of the East pasture; BA cows showed higher selection of this vegetation type than RC counterparts in both absolute (E 0.19 vs. -0.20) and relative (rank # 4 vs. 6) terms (Table 1). Relative selection of three shrubland types (Sagebrush Scrub, Chamise Chaparral, and Red Shank Chaparral) was consistently greater for RC vs. BA cows (i.e. E rank for RC < E rank for BA), regardless of pasture (Table 1). A similar pattern was observed for a fourth shrubland type, the Upper Sonoran Mixed Chaparral; relative selection of this shrubland was greater for RC vs. BA cows in three of the four RCM pastures (Table 1). Interestingly, no instances of greater relative selection by BA vs. RC cows of any of the six shrubland types present at RCM were observed in this study (Table 1). Raramuri Criollo cows showed greater relative selection of coniferous forest vs. BA cows in three of the four study pastures (Table 1).

At DR, Red Angus cows exhibited greatest relative selection of grassland or riparian vegetation types, whereas for RC, grassland, riparian, or shrubland vegetation were the most selected (Table 2). Desert shrublands were the second most preferred vegetation type of RC cows in three of the five pastures grazed, whereas these same shrublands ranked second in preference for BA cows in only one pasture (Table 2). Nine of the 13 largest breed differences (i.e. electivity rank difference of 2 or more) in relative selection of a vegetation type occurred in shrublands (Table 2). RC exhibited greater relative selection than RA of greasewood, Gambel oak, and salt desert shrubland, whereas the opposite occurred in the case of juniper, big sagebrush, and desert shrub steppe. Large relative preference differences of grasslands occurred in Lavender (RC E rank < RA E rank) and Park (RA E rank < RC E rank). The remaining two instances of large relative selection differences between breeds occurred in riparian areas; in two of the five study pastures, RA cows showed considerably greater selection of Invasive Southwest Riparian Woodland and Shrubland vegetation than RC counterparts in both absolute (E 0.13 or 0.61 vs. -0.73 or 0.28 for RA and RC, respectively) and relative (rank # 2 vs. # 9 or 5 for RA and RC, respectively) terms (Table 2).

Vegetation selection data in this study were only subjected to qualitative comparisons; therefore, caution is required in the interpretation

Table 1

Selection of land cover types by Raramuri Criollo (RC) and Black Angus (BA) mature cows during winter, spring, summer, and fall (2018–2021) while grazing East, North, South, and West-Center pastures at Rancho Corta Madera. Ivlev's Electivity Index (*E*) values are shown where $-1 =$ avoidance, $0 =$ indifference, and $1 =$ selection of a given vegetation cover type). Relative electivity rank of each cover type ordered from most ($=1$) to least selected (largest rank number) cover type by cows of each breed within each pasture is also shown. Shaded cells show instances of relative electivity rank differences of two or more places. Bold cover type descriptors indicate instances where relative selection exhibited by RC was greater than that of BA cows in all or almost all instances.

Vegetation Cover Type	East				North				South				West-Center			
	RC		BA		RC		BA		RC		BA		RC		BA	
	<i>E</i>	Rank	<i>E</i>	Rank	<i>E</i>	Rank	<i>E</i>	Rank	<i>E</i>	Rank	<i>E</i>	Rank	<i>E</i>	Rank	<i>E</i>	Rank
Unvegetated Habitat	0.57	3	0.74	3	0.12	4	0.00	4	0.13	3	-0.26	4	-0.69	3	-0.77	3
Diegan Coastal Sage Scrub					-0.52	5	-0.52	5								
Sagebrush Scrub	0.49	4	0.08	5	-0.79	6	-0.70	7								
Upper Sonoran Mixed Chaparral	-0.83	8	-0.82	9	-0.87	7	-0.98	8	-0.99	5	-0.98	6	-0.94	4	-0.93	4
Chamise Chaparral	-0.98	9	-0.98	10					-0.85	4	-0.76	5				
Red Shank Chaparral	-1.00	10	-1.00	11												
Montane Chaparral	-1.00	10	-0.98	10												
Flat Topped Buckwheat	-0.23	7	0.02	7												
Valley and Foothill Grassland	0.65	2	0.65	2	0.85	1	0.85	2	0.50	1	0.58	1	0.38	1	0.34	1
Meadow and Seep	0.87	1	0.86	1	0.50	2	0.95	1	0.08	2	0.23	2				
Cismontane Woodland	-0.20	6	0.19	4	0.27	3	0.51	3								
Mixed Oak Woodland					-1.00	8	-1.00	9								
Undifferentiated Open Woodland	-0.98	9	-0.80	8												
Lower Montane Coniferous Forest	0.30	5	0.07	6	-0.33	5	-0.61	6	0.13	3	0.15	3	-0.24	2	-0.13	3

Table 2

Selection of vegetation cover types by Raramuri Criollo (RC) and Red Angus (RA) mature cows during late fall, winter, and early spring (2018–2021) while grazing Corral Pocket, Creek, Davis, Lavender, and Park pastures at the Dugout Ranch. Ivlev's Electivity Index (*E*) values are shown where $-1 =$ avoidance, $0 =$ indifference, and $1 =$ selection of a given land cover type. Relative electivity rank of each cover type ordered from most ($=1$) to least selected (largest rank number) cover type by cows of each breed within each pasture is also shown. Shaded cells show instances of relative electivity rank differences of two or more places (dark grey cells, relative electivity of RC > RA; light grey cells: relative electivity of RA > RC). Bold cover type descriptors indicate instances where relative selection exhibited by RC was greater than that of RA cows in all or almost all instances.

Cover Type	Corral Pocket		Creek		Davis		Lavender		Park											
	RC		RA		RC		RA		RC		RA									
	<i>E</i>	Rank	<i>E</i>	Rank	<i>E</i>	Rank	<i>E</i>	Rank	<i>E</i>	Rank	<i>E</i>	Rank								
Colorado Plateau Mixed Bedrock Canyon and Tableland	-0.95	8	-0.92	9	-0.93	10	-0.75	9	-0.69	7	-0.62	8	-0.82	10	-0.72	9	-0.42	7	-0.42	8
Inter-Mountain Basins Active and Stabilized Dune													-0.51	7	-0.52	8	-0.91	11	-0.91	10
Colorado Plateau Pinyon-Juniper Woodland	-0.99	9	-1	10	-0.98	11	-0.92	10	-0.80	10	-0.69	9	-0.55	8	-0.43	7	-1	13	-1	12
Rocky Mountain Gambel Oak-Mixed Montane Shrubland																	0.59	2	-0.16	6
Colorado Plateau Pinyon-Juniper Shrubland	-0.95	8	-0.85	7	-0.84	9	-0.57	8	-0.93	11	-0.61	7	-0.32	6	-0.23	6	-0.53	8	-0.27	7
Inter-Mountain Basins Big Sagebrush Shrubland	-0.87	6	-0.72	6	-0.45	7	-0.10	6	-0.32	6	-0.36	4	-0.74	9	-0.73	10	-0.79	9	-0.67	9
Colorado Plateau Blackbrush-Mormon-tea Shrubland	0.15	2	0.12	2	0.15	2	0.02	4	0.05	3	-0.17	3	0.56	3	0.39	3	-0.01	5	0.00	3
Inter-Mountain Basins Mixed Salt Desert Scrub	-0.99	9	-1	10	-0.01	5	-0.05	5	-0.19	5	-0.65	6	-1	11	-0.93	11	-0.85	10	-1	12
Inter-Mountain Basins Semi-Desert Shrub Steppe	-0.67	5	-0.34	4	-0.71	8	-0.33	7	-0.70	8	-0.47	5	0.51	4	0.09	4	-0.97	12	-0.92	11
Inter-Mountain Basins Semi-Desert Grassland	0.50	1	0.44	1	0.09	3	0.15	2	0.42	2	-0.17	3	0.69	2	-0.17	5	0.29	4	0.32	2
Rocky Mount. Lower Montane Riparian Wood & Shrub	-0.59	4	-0.15	3	0.41	1	0.36	1	0.66	1	0.72	1	0.80	1	0.84	1	0.60	1	0.40	1
Inter-Mountain Basins Greasewood Flat	-0.25	3	-0.49	5	0.06	4	0.14	3	-0.15	4	-0.75	10					0.35	3	-0.14	4
Invasive Southwest Riparian Woodland and Shrubland	-0.90	7	-0.90	8	-0.27	6	-0.33	7	-0.73	9	0.13	2	0.28	5	0.61	2	-0.33	6	-0.15	5

of patterns observed. Somewhat unsurprisingly, cows of both breeds appeared to prefer grassland vegetation at both sites. However, instances where RC showed greater relative preference for shrubland vegetation than British counterparts occurred more frequently than the converse. The two largest relative selection differences documented in this study occurred in shrubland (greasewood flat) and riparian habitats (invasive SW riparian woodland& shrubland) of Davis pasture at the

Dugout Ranch (Table 2). Compared to RA cows, RC showed considerably greater relative selection of the shrubland type (*E* rank # 4 vs # 10 for RC vs. RA) and substantially lower preference for the riparian type (*E* rank # 9 vs # 2 for RC vs. RA). Ranchers who raise Criollo cattle often report that these animals are observed browsing more often than conventional beef breeds. Our data provide tentative support for this observation with a few caveats. Criollo cows at both sites showed greater

relative preference for grasslands than shrublands, but in most instances appeared to exhibit greater tendency to forage in shrublands compared with British beef cows. Relative selectivity of shrub-dominated vegetation by RC cows varied depending on the shrubland species present. In several instances (but not always), British cows showed greater selection of riparian areas compared to RC cattle, a pattern that if confirmed, could have significant conservation implications for Southwest ranching systems. Further quantitative analyses of resource selection patterns as conducted by Peinetti et al. (2011) or Nyamuryekung'e et al. (2022) would be needed to determine the influence of vegetation type vs. other biophysical features of the grazing environment (e.g. plant phenology, topography, distance to drinkers) on feeding site selection patterns of Criollo vs. British breed at our study sites.

4. Conclusions

Foraging pattern differences between Raramuri Criollo and commercial beef cattle previously reported in experiments conducted in the Chihuahuan Desert were observed at our study sites in the California Chaparral and Colorado Plateau. This study provides additional support for the recommendation made by the Fourth National Climate Assessment of the United States (Reidmiller et al., 2018) in regards to the value of Criollo cattle as a tool to increase climate adaptation and strengthen the resilience of ranching families across the Southwest. Further research is needed to assess the potential of Criollo cattle to strengthen the financial sustainability of ranching systems and reduce the environmental footprint of beef production in the ecosystems where our study was conducted.

5. Disclaimer

Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jaridenv.2023.104975>.

References

- Anderson, D.M., Estell, R.E., Gonzalez, A.L., Cibils, A.F., Torell, L.A., 2015. Criollo cattle: heritage genetics for arid landscapes. *Rangelands* 37, 62–67.
- Batschelet, E., 1981. *Circular Statistics in Biology*. Academic Press, London.
- Benhamou, S., 2004. How to reliably estimate the tortuosity of an animal's path: straightness, sinuosity, or fractal dimension? *J. Theor. Biol.* 229, 209–220.
- Bouissou, M.F., 1972. Influence of body weight and presence of horns on social rank in domestic cattle. *Anim. Behav.* 20, 474–477.
- Browning, D.M., Spiegel, S., Estell, R.E., Cibils, A.F., Peinetti, H.R., 2018. Integrating space and time: a case for phenological context in grazing studies and management. *Frontiers Agricultural Sci. Eng.* 5, 44–58.
- Brunson, M.W., Huntsinger, L., 2008. Ranching as a conservation strategy: can old ranchers save the new west? *Rangel. Ecol. Manag.* 61, 137–147.
- Buckley Biggs, N., 2022. Drivers and constraints of land use transitions on Western grasslands: insights from a California mountain ranching community. *Landsc. Ecol.* 37, 1185–1205.
- Cibils, A.F., Boykin, K.G., Cooper, B.F., Miller, J.A., Encinas, A.M., 2008. Monitoring Heifer Grazing Distribution at the Valles Caldera National Preserve *Rangelands*, 30, pp. 19–23.
- Concostrina-Zubiri, L., Huber-Sannwald, E., Martínez, I., Flores, J.L.F., Reyes-Agüero, J. A., Escudero, A., Belnap, J., 2014. Biological soil crusts across disturbance-recovery scenarios: effect of grazing regime on community dynamics. *Ecol. Appl.* 24, 1863–1877.
- Duniway, M.C., Benson, C., Nauman, T.W., Knight, A., Bradford, J.B., Munson, S.M., Witwicks, D., Livensperger, C., Van Scoyoc, M., Fisk, T.T., Thoma, D., Miller, M.E., 2022. Geologic, geomorphic, and edaphic underpinnings of dryland ecosystems: Colorado Plateau landscapes in a changing world. *Ecosphere* 13, e4273.
- Estell, R., 2021. The genesis of the Jornada Criollo cattle program. *J. Arid Environ.* 193, 104563.
- Estell, R.E., Nyamuryekung'e, S., James, D.K., Spiegel, S., Cibils, A.F., Gonzalez, A.L., McIntosh, M.M., Romig, K., 2022. Diet selection of Raramuri Criollo and Angus x hereford crossbred cattle in the Chihuahuan Desert. *J. Arid Environ.* 205, 104823.
- Finger-Higgins, R., Duniway, M.C., Fick, S., Geiger, E.L., Hoover, D.L., Pfennigwerth, A. A., Van Scoyoc, M.W., Belnap, J., 2022. Decline in biological soil crust N-fixing lichens linked to increasing summertime temperatures. *Proc. Natl. Acad. Sci. USA* 119, e2120975119.
- Fortin, D., 2003. Searching behavior and use of sampling information by free-ranging bison (*Bos bison*). *Behav. Ecol. Sociobiol.* 54, 194–203.
- Gentner, B.J., Tanaka, J.A., 2002. Classifying federal public land grazing permittees. *J. Range Manag.* 55, 2–11.
- Godde, C.M., Boone, R.B., Ash, A.J., Waha, K., Sloat, L.L., Thornton, P.K., Herrero, M., 2020. Global rangeland production systems and livelihoods at threat under climate change and variability. *Environ. Res. Lett.* 15, 044021.

- Gong, Q., Cao, H., Cibils, A.F., Nyamuryekung'e, S., McIntosh, M.M., Continanza, F.G., 2020. GRAZETOOLS: A Set of Tools for Analyzing Livestock Behavior Using GPS Data. AGU Fall Meeting Online.
- Gonzalez, P., Garfin, G.M., Breshears, D.D., Brooks, K.M., Brown, H.E., Elias, E.H., Gunasekara, A., Huntly, N., Maldonado, J.K., Mantua, N.J., Margolis, H.G., McAfee, S., Middleton, B.R., Udall, B.H., 2018. Chapter 25: Southwest. U.S. Global Change Research Program, Washington, DC, USA.
- Grandin, T., 2014. Behavioral principles of handling cattle and other grazing animals under extensive conditions. In: Grandin, T. (Ed.), *Livestock Handling and Transport*, fourth ed. CABI International, Wallingford, UK, pp. 39–64.
- Hereford, R., Webb, R.H., 1992. Historic variation of warm-season rainfall, Southern Colorado Plateau. *Southwestern U.S.A. Climatic Change* 22, 239–256.
- Herrera Conegliano, O.A., Blanco, L.J., Utsumi, S.A., Cibils, A.F., Cendoya, M.G., Jaimes, F., Moltoni, A.F., Ricci, P., 2022. Foraging behavior of Argentine Criollo and Angus cows grazing desert rangelands in the Arid Gran Chaco region of Argentina. *this issue. J. Arid Environ.* (In review).
- Holechek, J.L., Pieper, R.D., Herbel, C.H., 2011. *Range Management: Principles and Practices*, sixth ed. Prentice Hall, New Jersey.
- Holland, R.F., 1986. In: *Fish, S.o.C.D.o.G.a. (Ed.), Preliminary Descriptions of the Terrestrial Natural Communities of California*. <https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=75893>.
- Huntsinger, L., Hopkins, P., 1996. Viewpoint: sustaining rangeland landscapes: a social and ecological process. *J. Range Manag.* 49, 167–173.
- Huntsinger, L., Johnson, M., Stafford, M., Fried, J., 2010. Hardwood rangeland landowners in California from 1985 to 2004: production, ecosystem services, and permanence. *Rangel. Ecol. Manag.* 63, 324–334.
- Huntsinger, L., Sayre, N.F., 2007. Introduction: the working landscapes special issue. *Rangelands* 29, 3–4.
- Jacobs, J., 1974. Quantitative measurement of Food selection: a modification of the forage ratio and ivlev's electivity index. *Oecologia* 14, 413–417.
- Krysl, L.J., Hess, B.W., 1993. Influence of supplementation on behavior of grazing cattle. *J. Anim. Sci.* 71, 2546–2555.
- Langley, R.B., 1999. Dilution of Precision. *GPS World*, pp. 52–59.
- Larson, S., Barry, S., Bush, L., 2015. *Bay Area Ranching Heritage: a Continuing Legacy. Understanding Working Rangelands Series. ANR Publication 8528. University of California - Division of Agriculture and Natural Resources*, p. 5.
- Lechowicz, M.J., 1982. The sampling characteristics of electivity indices. *Oecologia* 52, 22–30.
- Liffmann, R.H., Huntsinger, L., Forero, L.C., 2000. To ranch or not to ranch: home on the urban range? *J. Range Manag.* 53, 362–370.
- Lowry, J.H., Ramsey, R.D., Boykin, K., Bradford, D., Comer, P., Falzarano, S., Kepner, W., Kirby, J., Langs, L., Prior-Magee, J., Manis, G., O'Brien, L., Pohn, K., Rieth, W., Sajwaj, T., Schrader, S., Thomas, K.A., Schrupp, D., Schultz, K., Thompson, B., Wallace, C., Velazquez, C., Waller, E., Wolk, B., 2005. *Southwest Regional Gap Analysis Project: Final Report on Land Cover Mapping Methods. RS/GIS Laboratory, Utah State University, Logan, UT*, p. 50.
- McIntosh, M.M., Cibils, A.F., Estell, R.E., Nyamuryekung'e, S., González, A.L., Gong, Q., Cao, H., Spiegel, S.A., Soto-Navarro, S.A., Blair, A.D., 2021. Weight gain, grazing behavior and carcass quality of desert grass-fed Raramuri Criollo vs. crossbred steers. *Livest. Sci.* 249, 104511.
- McIntosh, M.M., Gonzalez, A.L., Cibils, A.F., Estell, R.E., Nyamuryekung'e, S., Rodriguez Almeida, F.A., Spiegel, S., 2020. A phenotypic characterization of Raramuri Criollo cattle introduced into the southwestern United States. *Arch. Latinoam. Prod. Anim.* 28, 111–119.
- McIntosh, M.M., Spiegel, S.A., McIntosh, S.Z., Estell, R.E., Castano Sanchez, J., Steele, C. M., Elias, E.H., Brown, J.R., Cibils, A.F., 2023. Matching beef cattle breeds to the environment for desired outcomes in a changing climate: a systematic review with meta-analysis. *this issue J. Arid Environ.* (In review).
- Nyamuryekung'e, S., Cibils, A.F., Estell, R.E., McIntosh, M., VanLeeuwen, D., Steele, C., González, A.L., Spiegel, S., Reyes, L.A., Rodríguez Almeida, F.A., Anderson, M., 2021. Foraging behavior and body temperature of heritage vs. commercial beef cows in relation to desert ambient heat. *J. Arid Environ.* 193, 104565.
- Nyamuryekung'e, S., Cibils, A.F., Estell, R.E., VanLeeuwen, D., Spiegel, S., Steele, C., González, A.L., McIntosh, M.M., Gong, Q., Cao, H., 2022. Movement, activity, and landscape use patterns of heritage and commercial beef cows grazing Chihuahuan Desert rangeland. *J. Arid Environ.* 199, 104704.
- Nyamuryekung'e, S., Cibils, A.F., Estell, R.E., VanLeeuwen, D., Steele, C., Estrada, O.R., Almeida, F.A.R., González, A.L., Spiegel, S., 2020. Do young calves influence movement patterns of nursing Raramuri Criollo cows on rangeland? *Rangel. Ecol. Manag.* 73, 84–92.
- Oviedo, J.L., Huntsinger, L., Campos, P., Caparros, A., 2012. Income value of private amenities assessed in California oak woodlands. *Calif. Agric.* 66, 91–96.
- Peinetti, H.R., Fredrickson, E.L., Peters, D.P.C., Cibils, A.F., Roacho-Estrada, J.O., Laliberte, A.S., 2011. Foraging behavior of heritage versus recently introduced herbivores on desert landscapes of the American Southwest. *Ecosphere* 2.
- R Core Team, 2021. *R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria*. <https://www.R-project.org/>.
- Reidmiller, D.R., Avery, C.W., Easterling, D.R., Kunkel, K.E., Lewis, K.L.M., Maycock, T. K., Stewart, B.C. (Eds.), 2018. *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment. U.S. Global Change Research Program, Washington, DC, USA*.
- Roacho Estrada, O., Rodriguez Almeida, F.A., Utsumi, S.A., Gonzalez, A.L., Fredrickson, E.L., Bezanilla Enriquez, G.A., 2023. Grazing behavior of Raramuri Criollo vs. crossbred cows on rangelands of New Mexico (USA) and Chihuahua (Mexico). *this issue. J. Arid Environ.* (In review).
- Root, H.T., Miller, J.E.D., Rosentreter, R., 2020. Grazing disturbance promotes exotic annual grasses by degrading soil biocrust communities. *Ecol. Appl.* 30, e02016.
- Rouda, R.R., Anderson, D.M., Murray, L.W., Smith, J.N., 1990. Distance traveled by free-ranging supplemented and non-supplemented lactating and non-lactating cows. *Appl. Anim. Behav. Sci.* 28, 221–232.
- Rowe, H.L., Bartlett, E.T., Swanson Jr., L.E., 2001. Ranching motivations in two Colorado counties. *J. Range Manag.* 54, 314–321.
- Russell, M.L., Bailey, D.W., Thomas, M.G., Witmore, B.K., 2012. Grazing distribution and diet quality of Angus, brangus, and brahman cows in the Chihuahuan Desert. *Rangel. Ecol. Manag.* 65, 371–381.
- SANDAG, 2013. *Data Basin, San Diego*. <https://databasin.org/datasets/ff2825e4cd144125b4acd5e15755cdf/>.
- Sawalhah, M.N., Cibils, A.F., Maladi, A., Cao, H., Vanleeuwen, D.M., Holechek, J.L., Black Rubio, C.M., Wesley, R.L., Endecott, R.L., Mulliniks, T.J., Petersen, M.K., 2016. Forage and weather influence day versus nighttime cow behavior and calf weaning weights on rangeland. *Rangel. Ecol. Manag.* 69, 134–143.
- Schauer, C.S., Bohnert, D.W., Ganskopp, D.C., Richards, C.J., Falck, S.J., 2005. Influence of protein supplementation frequency on cows consuming low-quality forage: performance, grazing behavior, and variation in supplement intake. *J. Anim. Sci.* 83, 1715–1725.
- Smith, A.H., Martin, W.E., 1972. Socioeconomic behavior of cattle ranchers, with implications for rural community development in the West. *Am. J. Agric. Econ.* 54, 217–225.
- Spiegel, S., Cibils, A.F., Bestelmeyer, B.T., Steiner, J.L., Estell, R.E., Archer, D.W., Auvermann, B.W., Bestelmeyer, S.V., Boucheron, L.E., Cao, H., Cox, A.R., Devlin, D., Duff, G.C., Ehlers, K.K., Elias, E.H., Gifford, C.A., Gonzalez, A.L., Holland, J.P., Jennings, J.S., Marshall, A.M., McCracken, D.I., McIntosh, M.M., Miller, R., Musumba, M., Paulin, R., Place, S.E., Redd, M., Rotz, C.A., Tolle, C., Waterhouse, A., 2020. Beef production in the southwestern United States: strategies toward sustainability. *Front. Sustain. Food Syst.* 4.
- Spiegel, S., Estell, R.E., Cibils, A.F., Armstrong, E., Blanco, L.J., Bestelmeyer, B.T., *this issue. Can heritage Criollo cattle promote sustainability in a changing world? . J. Arid Environ.*
- Spiegel, S., Estell, R.E., Cibils, A.F., James, D.K., Peinetti, H.R., Browning, D.M., Romig, K.B., Gonzalez, A.L., Lyons, A.J., Bestelmeyer, B.T., 2019. Seasonal divergence of landscape use by heritage and conventional cattle on desert rangeland. *Rangel. Ecol. Manag.* 72, 590–601.
- Sproul, F., Keeler-Wolf, T., Gordon-Reedy, P., Dunn, J., Klein, A., Harper, K., 2011. In: *Game, A.a.C.D.o.F.a. (Ed.), Vegetation Classification Manual for Western San Diego County*. https://sdmmp.com/upload/projects/20160330_2357_94.pdf (San Diego).
- Sulak, A., Huntsinger, L., 2007. Public land grazing in California: untapped conservation potential for private lands? *Rangelands* 29, 9–12.
- Torell, G.L., Torell, L.A., Enyinnaya, J., Spiegel, S., Estell, R.E., Cibils, A.F., Anderson, D. M., Gonzalez, A.L., 2023. Economics of Raramuri Criollo and British crossbred cattle production in the Chihuahuan Desert: effects of grazing distribution and finishing strategy. *this issue J. Arid Environ.* (In review).
- USDA-NRCS, 2022. In: *Staff, S.S. (Ed.), Web Soil Survey*. <http://websoilsurvey.nrcs.usda.gov>.
- USEPA, 2022. *US Environmental Protection Agency*. <https://www.epa.gov/climate-indicators/climate-change-indicators-wildfires>.
- Utah Climate Center, 2022. *University, U.S.* <https://climate.usu.edu/>
- Wesley, R.L., Cibils, A.F., Mulliniks, J.T., Pollak, E.R., Petersen, M.K., Fredrickson, E.L., 2012. An assessment of behavioural syndromes in rangeland-raised beef cattle. *Appl. Animal Behaviour Sci.* 139, 183–194.
- Western Regional Climate Center, 2022. *Canyonlands-the needle. Utah (421168)*. <https://wrcc.dri.edu/cgi-bin/cliMAIN.pl?ut1168>.
- Williams, A.P., Cook, B.I., Smerdon, J.E., 2022. Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. *Nat. Clim. Change* 12, 232–234.