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Weight gain, grazing behavior and carcass quality of desert grass-fed Rarámuri Criollo vs. crossbred steers☆

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ABSTRACT

Rarámuri Criollo cattle producers often crossbreed their cows with improved beef-breed bulls and/or retain and develop their yearlings on rangeland because of limited weaned calf markets, however it is unknown if Rarámuri Criollo steers exhibit marketable weight gains and carcass qualities, *or* desirable grazing behaviors documented in cows of this biotype. We evaluated two cohorts (cohort: 1 = 31, 2 = 26) of Rarámuri Criollo (JRC), Mexican Criollo (MC) and Criollo × beef-breed crossbred (XC) steers to investigate effects of biotype on growth, carcass traits, and landscape utilization. Steers were weighed approximately once every 2-mo and average daily gains (ADG) calculated. Nine JRC and XC steers per cohort were monitored at 5-min intervals via global positioning systems (GPS) for 1-mo during winter (2015–16) and late-summer (2016–17). Weight and carcass data were analyzed using mixed measures procedures to identify differences between biotype through time. Discriminant analyses were conducted to determine whether grazing behaviors could be discriminated among: 1) JRC and XC steers and JRC cows; 2) steers by season (winter vs. summer); and 3) steers of cohort 1 and 2. Final live and carcass weights of XC were greater than JRC and MC, but all were market ready at 30-mo following a grass-finishing protocol. Carcass quality and ADG were not different among biotypes. Steers were discriminated into different season or cohort groups based on grazing behavior differences but JRC and XC steers exhibited grazing patterns that were similar to those previously observed in JRC cows. Our results suggest that JRC, MC, and XC steers can be developed to slaughter weights in 30-mo using a rangeland-based grass-fed protocol, and that JRC and XC steers exhibit desirable grazing behaviors previously observed in JRC cows.

1. Introduction

Most climate models predict that the American Southwest will become increasingly hotter and drier with more variable precipitation regimes, (Cook et al., 2015; Joyce et al., 2017; Williams et al., 2020) which will accelerate shrub encroachment (Gherardi and Sala, 2015) and will likely continue to cause significant declines in forage resources for livestock (McIntosh et al., 2019). Use of low-input desert-adapted

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beef cattle biotypes, such as Rarámuri Criollo cattle (Anderson et al., 2015), is one of several climate adaptation strategies gaining momentum among desert ranchers (Elias et al., 2020; Holechek et al., 2020; Scasta et al., 2016; Spiegal et al., 2019). Viability of these enterprises increasingly depends on producers' willingness to implement climate-smart management approaches (Briske et al., 2015; Estell et al., 2012) to meet ever-increasing demand for healthy beef products (Spiegal et al., 2020).

Criollo cattle are descendants of Andalusian cattle brought to the new world by early explorers (Anderson et al., 2015). Rarámuri Criollo cattle (De Alba Martinez, 2011), a biotype from the Copper Canyon in Chihuahua, México, exhibits a number of desirable foraging habits when grazing hot desert environments of the American Southwest (Anderson et al., 2015; Nyamuryekung'e et al., 2021; Peinetti et al., 2011; Spiegal et al., 2019). Studies that compared grazing behavior of Angus × Hereford (AH) and Rarámuri Criollo cows introduced from the Copper Canyon to the Jornada Experimental Range in southern New Mexico, USA (hereafter Jornada Rarámuri Criollo, JRC), have shown that JRC explore larger areas of a pasture and travel further from water during times of forage dormancy, when vegetation and soils are most vulnerable (Peinetti et al., 2011; Spiegal et al., 2019). This has led researchers to speculate that raising Criollo cattle may be a way to produce beef while exerting a lighter environmental footprint on desert rangeland (McIntosh et al., 2020).

Although Rarámuri Criollo are believed to be better suited for beef production compared to the smaller-framed and commonly available Corriente cattle selected and used for rodeo sports (Anderson et al., 2015; Ortega-Ochoa et al., 2008), JRC calves (like their Corriente counterparts) grow slowly and are usually too light to enter the mainstream beef market at weaning (weaning weight rarely exceeds 154.1 ± 2.2 kg, unpublished data). Therefore, ranchers raising JRC cattle must often retain weaned calves until they reach 400–500 kg, typically at about 28–30 months of age (Anderson et al., 2015). The same is generally true of Corriente and other Mexican Criollo calves, although these biotype-groups are thought to reach even lighter 30-month weights (NACA, 2020). An alternative production model used by cow-calf producers who raise Criollo cattle is to cross their mother cows with improved beef breed bulls to obtain faster-growing crossbred calves that reach heavier weights at weaning (~227 kg) and can either be sold to feeders for backgrounding or finishing, or retained on rangeland and finished on grass. Crossbreeding is also common among producers in northern México (Velázquez et al., 2008) who seek the advantages of hybrid vigor, such as increased size in F1 calves (first generation crossbreds), as well as desirable genetic traits (rusticity) retained from ancestral breeds (Porto-Neto et al., 2016). There is a paucity of data on growth rates of Criollo (either JRC or other) or Criollo crossbred calves that are developed on desert rangeland and no studies to date have determined whether weaned calves (either Criollo or crossbred) exhibit the desirable foraging behavior traits observed in mature JRC cows (Nyamuryekung'e et al., 2021; Peinetti et al., 2011; Spiegal et al., 2019) or how desert vegetation phenology might affect grass-fed steer weight gains. This information is urgently needed to assess the economic sustainability of raising Mexican Criollo cattle on southwestern rangelands (Enyinnaya, 2016; Spiegal et al., 2020; Torell et al., In Preperation)

Producers who raise Criollo or Criollo crossbred cattle are frequently interested in producing beef to supply the growing demand for grass-fed meat in the United States (Barnes, 2011; Spiegal et al., 2020). The US grass-finished, local, and organic meats market was valued at $1 to 3 billion in 2015 (Cheung and McMahon, 2017) and is estimated to be growing at an annual rate of 100%; however, only 20% of US grass-fed beef is produced in the western states (Cheung and McMahon, 2017). No studies to date have documented the feasibility of finishing steers on desert forages and very little is known about the quality of meat that could be expected from desert grass-fed Criollo or Criollo crossbred animals. Case study analyses suggest that there could be economic benefits associated with raising grass-finished JRC yearling steers on desert rangeland compared to conventional Angus × Hereford counterparts (Enyinnaya, 2016) but conclusions of these studies are severely limited by lack of data on weight gains and carcass quality of weaned yearling Criollo (either JRC or other) and Criollo crossbred steers.

We conducted a two-year study in the Chihuahuan Desert that addressed the following questions: 1) Can JRC, Mexican Criollo (MC), and Criollo crossbred (XC) yearling steers raised on desert forages reach slaughter weights at 30 months of age, and do they gain weight at similar rates?; 2) Do rangeland-developed JRC and XC yearling steers exhibit the desirable landscape use patterns previously observed in JRC cows?; and 3) Do slaughtered grass-fed JRC, MC, and XC steers exhibit similar carcass and meat quality? We predicted that weight gains of XC would be greater than those of JRC or MC and that landscape use patterns of JRC and XC groups would be similar.

2. Materials and methods

2.1. Study area description

This study was conducted at the Jornada Experimental Range (JER; 32°37' N; 106°40' W) ~ 40 km north of Las Cruces, New Mexico, USA. The JER is approximately 78 104 ha and our experiment pasture was approximately 3 215 ha in size with an average elevation of 1200 m. The JER is located in the northern portion of the Chihuahuan Desert between the Rio Grande River (west) and the San Andres mountain range (east) where the climate is arid with warm summers and mild winters, and an average of ~230 frost-free days. The average annual temperature is 16.9 °C and average annual precipitation is approximately 248 mm. Rainfall events primarily occur during the monsoon season (July through September). Soils of the north western JER are predominantly of the Berino-Bucklebar Association (sandy) and vegetation of the study area includes perennial grasses such as black grama (*Bouteloua eriopoda* Torr.), dropseeds (*Sporobolus* spp.), threeawns (*Aristida* spp.), tobosa (*Pleuraphis mutica* Buckley), and burrograss (*Schleropogon brevifolius* Phil.). Shrubs of our study area include honey mesquite (*Prosopis glandulosa* Torr.), soap-tree yucca (*Yucca elata* Engelm.), broom snakeweed (*Gutierrezia sarothrae* [Pursh] Britton & Rusby), creosote bush (*Larrea tridentate* [DC.]) and fourwing saltbush (*Atriplex canescens* [Pursh] Nutt.).

Study area descriptions are provided by Spiegal et al. (2019). Four permanent drinkers and five dirt tanks (ephemeral water during late summer) were present in this pasture that was also intersected by a network of dirt roads as well as six small grazing exclosures. Most of the pasture (99.63%) was within 3.2 km (2 mi) from a drinker-watering source, the point at which cattle use begins to diminish (Holechek, 1991).

2.2. Animals

Animal handling protocols were approved by the New Mexico State University Institutional Animal Care and Use Committee (Protocol 2016–019). Two cohorts of yearling steers totaling 57 Jornada Rarámuri Criollo (JRC), Criollo × beef breed crossbreds (XC) and Mexican Criollo (MC; examples provided in Fig. 1) were monitored over a two-and-a-half-year period (December 2015 – January 2017) for weight gain and grazing behavior (Table 1). Jornada Rarámuri Criollo steers in this study were sourced from the USDA-ARS Jornada Experimental Range herd, which was imported to the ranch from the Chiapas – Temeris region of the Copper Canyon, México in 2005. Mexican Criollo (those not from the JER herd) used in this study were sourced from two Mexican ranches: Rancho el Nogal in Yeppachi, Chihuahua (cohort 1; C1) and Rancho Las Mesas de Las Borregas in Cuauhtémoc, Chihuahua (cohort 2; C2). Genotype history of the Mexican Criollo used in this study is unknown and it is likely that the MC evaluated were genotypically similar to the JRC. However, due to the difficult-to-obtain nature of the Rarámuri Criollo from the Copper Canyon (Anderson et al., 2015) and the fact that larger framed MC are relatively easier to obtain, their evaluation alongside the

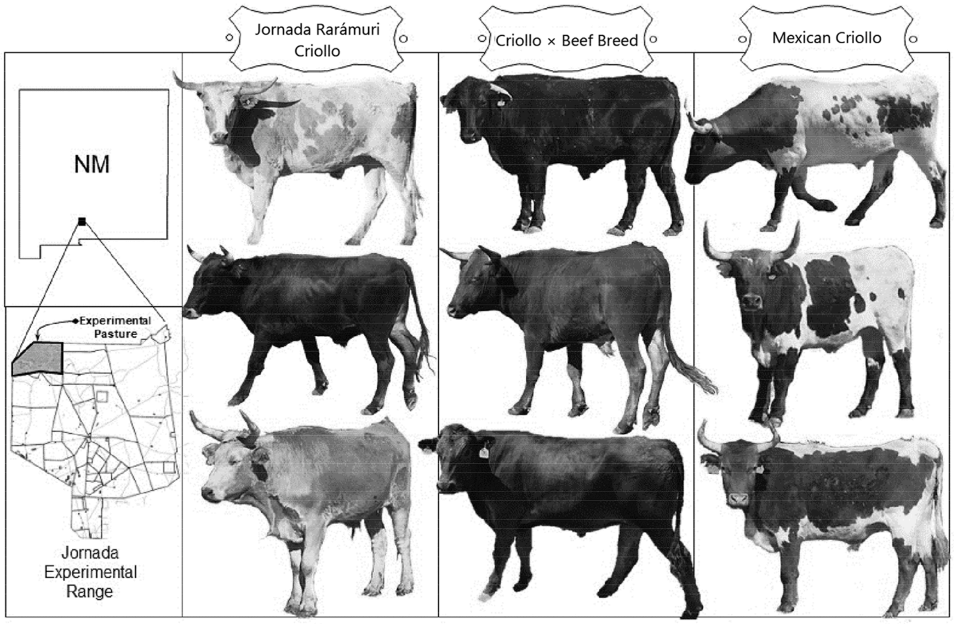

Fig. 1. Diagram of study site location (within New Mexico, USA and within the Jornada Experimental Range) and examples of mature steer biotypes: Jornada Rarámuri Criollo, Criollo x Beef Crossbreds (Brangus × Criollo [top and bottom] and Waguli × Criollo [center]), and Mexican Criollo from Cohorts 1 and 2.

Table 1
Mean values and standard errors of steer weights by biotype and cohort through time. Number of global positioning systems (GPS) deployed per biotype, date, and number of days.

date	biotype	Cohort 1 Mean Weight and SE (kg)	Approx. Age (mo)	Cohort 2 Mean Weight and SE (kg)	Approx. Age (mo)	GPS n	tracking days
12/4/2015	JRC	274.2 ± 4	15	233.7 ± 6.4	5	5	27
	MC	299.1 ± 3.8		179.9 ± 6.7		–	
	XC	312.7 ± 6.7		231.4 ± 11.53		5	
2/22/2016	JRC	278.8 ± 3.8	18	230 ± 6	7		
	MC	287.6 ± 4.1		184.2 ± 8.7			
	XC	308.5 ± 6.5		235 ± 9.31			
5/4/2016	JRC	290.6 ± 3	21	234.3 ± 5.3	10		
	MC	293.1 ± 3.8		190.3 ± 9.1			
	XC	327.2 ± 8.6		242.2 ± 9.89			
7/21/2016	JRC	335.2 ± 3.4	23	266.9 ± 5.3	12		
	MC	333.9 ± 4		227.4 ± 10.8			
	XC	368.9 ± 12.7		273.3 ± 9.68			
9/25/2016	JRC	349.7 ± 3	26	304 ± 5.9	15	3	56
	MC	341.1 ± 4.2		269.1 ± 10.9		–	
	XC	383.3 ± 11.2		323.4 ± 9.73		5	
12/1/2016	JRC	374 ± 5.2	28	317.3 ± 6.1	17	3	35
	MC	372.2 ± 5.1		293.5 ± 10.7		–	
	XC	408.7 ± 13.5		353.1 ± 11.63		4	
1/10/2017	JRC	346.2 ± 3.7	30	–			
	MC	352.3 ± 4.1		–			
	XC	385.4 ± 13.3		–			
3/17/2017	JRC	–	–	292.1 ± 6.7	19		
	MC	–	–	272.3 ± 11.3			
	XC	–	–	336.1 ± 9.99			
8/31/2017	JRC	–	–	346.6 ± 6.5	22	6	35
	MC	–	–	315.4 ± 24.7		–	
	XC	–	–	399.9 ± 9.56		3	
11/8/2017	JRC	–	–	417.1 ± 7.9	28		
	MC	–	–	361.9 ± 11.7			
	XC	–	–	492.1 ± 8.9			
2/1/2018	JRC	–	–	423.1 ± 7.84	30		
	MC	–	–	428.06 ± 9.83			
	XC	–	–	482.99 ± 9.19			

[a]JRC: Jornada Rarámuri Criollo (Cohort 1 : $n = 10$; cohort 2: $n = 8$)
[b]MC: Mexican Criollo (Cohort 1: $n = 12$; Cohort 2: $n = 7$)
[c]XC: Waguli × Criollo (Cohort 1: $n = 9$); Brangus × Criollo (Cohort 2: $n = 8$)

JRC herd is of great interest to a growing number of ranchers across the American Southwest who are seeking to raise larger-framed Mexican Criollo cattle.

The crossbreds available to conduct our study were Criollo × Waguli (cohort 1; sired by Criollo bulls on Waguli cows) and Criollo × Brangus (cohort 2; sired by Brangus bulls on Criollo cows) owned by two cooperating ranches: 47 Ranch, Bisbee, Arizona, USA and Evergreen Ranching, Black Hills, South Dakota, USA. Beef breeds used as crosses in this study differed between cohorts, but we reasoned that their genotypic parentage was suitable for replication because each are characterized by similar breed development histories and phenotypes. Waguli cattle were developed by the University of Arizona by crossing a *Bos indicus* based breed (Tuli) with an improved beef breed (Wagyu) in an attempt to create an animal that exhibited both high quality carcass and growth traits as well as heat tolerance (Garcia, 2013; Ibrahim et al., 2008). Brangus, too, were developed, originally, by the USDA –ARS station in Jeanerette, Louisiana by crossing a *Bos indicus* based breed (Brahman) with an improved beef breed (Angus; USDA, 1935) with the same goal of creating a heat-tolerant and high yielding animal. Though limited, studies that have compared Waguli to Brangus steer growth and carcass traits have shown few breed differences between mature weights, feed to gain ratios, dressing percentages, or other carcass merits (Garcia, 2013).

Steers were maintained on rangeland until 30 months of age to allow animals time to mature to slaughter weight. Few differences in major carcass grades and quality have been found in 30-month old steers developed in intensive vs. extensive production systems (Keane and Allen, 1998). Additionally, USDA 69 FR 1984 prohibits use of vertebral columns or skulls of cattle older than 30 months of age in Advanced Meat/Bone Separation Machinery (Coffey et al., 2005).

The recommended stocking rate for our study area is 5.14 ha • AUM^{-1} (USDA-NRCS 2017) and fewer than 30 steers, all weighing less than 500 kg, were placed in our 3215 ha experiment pasture at any point during this experiment. Thus, our study pasture was lightly stocked at all times. During the month prior to shipping, steers of each cohort were placed in smaller pastures and were provided *ad libitum* triticale hay.

Steers of both cohorts entered the trial with different weights (Table 1). Crossbred steers in cohort 1 had heavier initial weighs (312.7 ± 6.7 kg) than MC steers (299.1 ± 3.8 kg) and JRC steers (274.2 ± 4.0 kg; Table 1). Cohort 2 JRC steers had similar weights (233.7 ± 6.4 kg) than those of XC counterparts (231.4 ± 11.53 kg) and both of these were heavier than MC steers (179.9 ± 6.7 kg) at the onset of the study in cohort 2 (Table 1). Steers in both cohorts were weighed individually at approximately two-month intervals to the nearest half kilogram using a manual balance (Buffalo Scale Co.). Steers were fasted in pens overnight prior to weighing. Steers from C1 were shipped to the University of Arizona campus farm on January 09, 2017 and slaughtered shortly after on January 10, 2017. No meat quality data were available for steers in this cohort. Steers from C2 were shipped to Evergreen Ranch in Custer, South Dakota on February 1, 2018 where they were fed western wheat/ brome/ sweet clover grass-hay for approximately one month before being transported to Sturgis Meats in Sturgis, SD, USA and slaughtered on February 28, 2018. Subsequent analyses of carcass characteristics were performed by trained South Dakota State University personnel; C2 JRC, MC, and XC steers were analyzed for hot and cold carcass weights (kg), cooler shrink (%), adjusted preliminary yield grade, percent of kidney-pelvic-heart fat, ribeye area (cm^2), yield grade, and marbling score.

A subset of randomly selected JRC and XC steers within each cohort, and season were fitted with GPS collars (Lotek 3300, Lotek Wireless New Market Ontario, Canada) and monitored during winter (dormant vegetation) and late summer (end of growing season; Table 1). Collar GPS receivers were configured to log geolocation data at 5-min intervals. Grazing behavior of JRC and XC animals in both cohorts was monitored via GPS during winter and late summer (Table 1 and Fig. 4).

2.3. Data processing

GPS data collected during four periods over the course of this study were used to calculate 26 behavior variables including distance traveled, path sinuosity, area explored, activity (grazing, resting, traveling, travel: graze ratio), drinking behavior (time at water, time near water, and drinking frequency), and pasture use patterns (Table 2). The first two response variables were calculated for four daily time periods (night predawn hours, daytime hours, night post-sunset hours, and 24 h, day + night) using a Java program (GRAZEACT) tested by Sawalhah et al. (2016) and Gong et al. (2020). The Pythagorean Theorem was used to calculate distance traveled between two subsequent GPS points. Path sinuosity was inferred using the straightness index (Batschelet, 1981) that reflects the ratio of the distance between the first and last points for any time period and cumulative distances between consecutive points for the same period. A straightness index equal to zero indicates a highly sinuous path whereas an index equaling one indicates a straight path (Batschelet, 1981). The straightness index is a reliable indicator of tortuosity of a random search path (Benhamou, 1992). GRAZEACT was used to estimate area explored for the same four daily time periods (24-h, pre-dawn, daytime, post-sunset). Area explored was calculated as a minimum convex polygon (MCP) using a convex hull algorithm designed to encompass an individual animal's locations with internal angles less than 180°.

Activities including resting (movement velocity <2.34 m • min^{-1}), traveling (velocities >25 m • min^{-1}), and grazing (velocities >2.34 m • min^{-1} and <25 m • min^{-1}) were extracted using parameters tested by Nyamuryekung'e et al. (2020) that were partially adapted from (Augustine and Derner, 2013). Corresponding activities were assigned to each GPS point based on its velocity and overall activity budget was calculated by multiplying the number of GPS points classified into each activity class by fix time interval (5 min) and converted to h × day^{-1}.

A second Java program (GRAZEPIX) tested by Sawalhah et al. (2016) and described by Gong et al. (2020) was utilized to evaluate pasture use patterns. This software created a 30-m^2 pixel grid (50 841 total grid cells) of our study pasture and overlaid GPS fix locations where animals were presumed to be grazing (velocities ranging from 2.34 m • min^{-1} to 25 m • min^{-1}) to calculate percent of grazed pixels, pixel residence time, pixel revisit rate (pixel visits on different days), and pixel return interval (days between visits to the same pixel) for each animal. Pixels grazed (%) was calculated by determining the number of pixels grazed per animal and dividing by the sum of available pixels. Pixel revisit rates were calculated by summing the visits to each pixel on different days. Pixel return interval (days) was calculated by identifying the number of times an animal revisited a 30-m^2 pixel and calculating the number of days between visits. Pixel residence time (min × $visit^{-1}$) was calculated by summing the total of 5-minute grazing GPS fixes per cell per animal. These metrics were used to analyze pasture use pattern differences among biotypes, and between seasons and cohorts. To ensure consistency between sampling periods, only the first 20 d of each trial period were used to derive the four pasture use metrics described above.

Drinking behaviors including time at water (within 15 m from water, h × day^{-1}), time close to water (within 200 m from water, h × day^{-1}) and drinking frequency (visits × day^{-1} within 15-m of a drinker) during 24-h periods were calculated using the spatial join tool in ArcGIS 10 to merge GPS fix locations and buffered Euclidean distances from drinkers (ESRI, Redlands, CA). Metrics describing pasture use patterns in relation to the location of drinkers were based on Valentine (1947) and included time spent within 1.6 km of water (h × day^{-1}) and time spent between 1.6 and 3.2 km of water (h × day^{-1}) during 24-h periods and were also calculated in ArcGIS 10 (ESRI, Redlands, CA). Pasture use was expressed using Ivlev's (1961) electivity index $\left(E = \frac{r-p}{r+p}\right)$, where negative one = avoidance, zero = indifference, and one = selection, and where r is the proportion of time spent in each concentrically buffered drinker distance zone (ha) available within the pasture (p [total ha]; Jacobs, 1974).

Table 2
Mean values and standard errors of animal behavior variables.

		Winter Jornada Rarámuri Criollo	Crossbred	Late Summer Jornada Rarámuri Criollo	Crossbred
Distance Traveled (km)	Night Pre-Dawn hours	1.48 ± 0.17	1.58 ± 0.21	1.74 ± 0.11	1.42 ± 0.41
	Daytime hours	5.58 ± 0.15	5.70 ± 0.13	5.70 ± 0.27	5.12 ± 0.31
	Night Post-Sunset hours	3.26 ± 0.17	3.26 ± 0.17	2.37 ± 0.12	2.27 ± 0.09
	24 h	10.32 ± 0.37	10.79 ± 0.49	9.81 ± 0.41	8.81 ± 0.41
	Night : Day ratio	0.85 ± 0.06	0.89 ± 0.07	0.73 ± 0.05	0.74 ± 0.04
Path Sinuosity (SI)	Night Pre-Dawn hours	0.34 ± 0.04	0.36 ± 0.03	0.40 ± 0.04	0.41 ± 0.02
	Daytime hours	0.40 ± 0.00	0.40 ± 0.01	0.32 ± 0.03	0.40 ± 0.03
	Night Post-Sunset hours	0.64 ± 0.04	0.57 ± 0.03	0.46 ± 0.03	0.43 ± 0.03
	24 h	0.21 ± 0.01	0.22 ± 0.01	0.19 ± 0.02	0.23 ± 0.03
Area Explored (ha)	Night Pre-Dawn hours	32.11 ± 9.31	39.58 ± 9.17	24.72 ± 1.39	20.66 ± 2.20
	Daytime hours	219.23 ± 8.26	238.91 ± 6.12	163.10 ± 4.53	156.94 ± 8.82
	Night Post-Sunset hours	97.65 ± 11.47	115.83 ± 9.70	45.49 ± 5.96	53.73 ± 5.96
	24 h	441.61 ± 32.39	498.55 ± 22.89	282.80 ± 32.39	298.25 ± 23.56
Activity (h × day^{-1})	Grazing	8.39 ± 0.58	8.03 ± 0.57	8.71 ± 0.88	7.53 ± 0.60
	Resting	13.55 ± 0.53	13.71 ± 0.63	13.39 ± 0.89	14.76 ± 0.63
	Traveling	2.06 ± 0.13	2.28 ± 0.08	1.87 ± 0.08	1.73 ± 0.07
	Travel : Graze ratio	0.26 ± 0.03	0.29 ± 0.01	0.23 ± 0.02	0.23 ± 0.01
Drinking behavior	Time at water (h × day^{-1})	1.00 ± 0.08	1.16 ± 0.19	0.18 ± 0.04	0.24 ± 0.05
	Time close to water (h × day^{-1})	2.50 ± 0.28	2.88 ± 0.20	1.61 ± 0.34	2.37 ± 0.44
	Drinking frequency (visits × day^{-1})	0.95 ± 0.01	0.95 ± 0.01	0.73 ± 0.06	0.83 ± 0.06
Pasture use patterns	Grazing period (days)	31 ± 3.5	31 ± 3.5	46 ± 10.5	46 ± 10.5
	Pixels grazed (%)	4.63 ± 0.32	4.77 ± 0.32	4.56 ± 0.28	4.63 ± 0.38
	Pixel revisit rate (# visits)	1.16 ± 0.02	1.12 ± 0.01	1.43 ± 0.03	1.42 ± 0.03
	Pixel return interval (days)	10.09 ± 0.52	10.07 ± 0.34	12.58 ± 1.84	15.27 ± 1.86
	Time w/in 1.6 km of water (h × day^{-1})	18.43 ± 0.52	18.20 ± 0.51	21.83 ± 0.68	20.53 ± 0.80
	Time between 1.6 and 3.2 km of water (h × day^{-1})	5.51 ± 0.54	5.70 ± 0.56	2.21 ± 0.63	3.33 ± 0.76
	Time farther than 3.2 km of water (h × day^{-1})	0.06 ± 0.02	0.09 ± 0.03	0.04 ± 0.02	0.15 ± 0.06

Drinking behaviors were calculated using all GPS fix locations.

Steer weights were recorded to the closest half kilogram and were determined by averaging two weights recorded per steer per weighing date. Steers were fasted overnight and the entire group (cohort) of steers were passed through the scale twice during morning hours on weighing days (Table 1). Average daily gains (ADG) were calculated by subtracting the final weight prior to shipping (30 months of age) from the initial weight (when animals entered the study) and dividing the difference by the total number of days in the study. Partial ADG was also calculated for GPS-tracking periods by subtracting the final weight (from the end of the tracking period) from the initial weight (at the beginning of the tracking period) and dividing the difference by the total number of days in the tracking period (~ one month; Table 1). Kilograms of beef per hectare (kg × ha^{-1}) was calculated as the total weight gain per cohort between weight dates divided by the total hectares of our 3215 ha study pasture. Steer carcass characteristics were analyzed for C2 animals in March 2018.

Vegetation phenology is known to have strong effects on livestock performance on rangelands (Cruz and Ganskopp, 1998). To determine the relationship between vegetation phenology (greenness) and animal performance, we regressed MODIS Terra 16-day composite 250 m time-series Normalized Difference Vegetation Index (NDVI) products (MOD13Q1) against kilograms of beef per hectare. Our NDVI products spanned the entire study period. One NDVI tile (V006) was mosaicked and re-projected from sinusoidal projection to WGS 1984 UTM zone 13N. Each NDVI image was overlaid on our map and the mean NDVI of 30 pixels covering the study area was used to predict relative plant greenness per period. Kilograms of beef per hectare produced between weighing dates (described above) was regressed against maximum pasture NDVI for each period.

2.4. Statistical analyses

We used the mixed procedure in SAS 9.4 to analyze differences of final weights and ADG per biotype and cohort (SAS Institute, Cary, NC, USA). Data were analyzed assuming a completely randomized design. Biotype was considered a random effect in our model. The pdiff option in lsmeans was used to detect significant differences ($P \leq 0.05$) among biotypes and cohorts. We used the reg procedure in SAS 9.4 (SAS Institute, Cary, NC, USA) to analyze the relationship between beef production per hectare and pasture maximum NDVI for each cohort.

Discriminant function analysis (DA; McGarigal et al., 2000) is frequently used to classify animals into groups on the basis of multiple criteria such as the selection of diets (Hanley and Hanley, 1982; Ortega et al., 1997) or variation in behaviors (Bayley et al., 1997; Darden et al., 2003; Delgado, 2007). We used DA to determine if steers could be accurately discriminated into groups based on either biotype (JRC or XC), season (winter or late summer), or cohort (1 or 2) using a linear discriminant function. Stepwise discriminant function analysis was then conducted to identify the minimum set of behavior predictors (out of 26) able to classify individuals correctly into either biotype-, season-, or cohort- based groups. We also used DA to determine whether the behavior of JRC and XC steers in this study resembled that of JRC or Angus × Hereford (AH) cows in the Spiegal et al. (2019) experiment conducted in this same pasture in 2008. We expected that JRC cows and steers and XC steers would be discriminated into similar behavioral categories when compared against AH cows. Only three predictors measured in both this and the Spiegal et al. (2019) study were used in this analysis: 1) time spent grazing (h × day^{-1}), 2) distance traveled (km × day^{-1}), 3) and time spent close to a drinker (h × day^{1}).

The alpha level to enter and retain variables in the stepwise procedure was $P = 0.10$. The DISCRIM and STEPDISC procedures in SAS 9.4 (SAS Institute, Cary, NC, USA) were used to perform statistical analyses. Proportional prior probability of group membership was assumed (McGarigal et al., 2000) using the *priors = proportional* option in SAS 9.4 (SAS Institute, Cary, NC, USA). The *covariance = test* option in SAS 9.4 (SAS Institute, Cary, NC, USA) was also used to test for equal variance–covariance structure across groups and to determine the appropriateness of the use of linear discriminant function. Wilk's λ was used in the MANOVA F tests to determine whether groups classified on the basis of reduced sets of behavioral predictors were detectably different ($P \leq 0.05$). When classification into detectably different groups was achieved, cross validation was conducted to determine the error rate of the discriminant function using the *crossvalidate* option in SAS 9.4 (SAS

Institute, Cary, NC, USA). Standardized coefficients of the discriminant function were obtained using the *can out=scores* option in SAS 9.4 (SAS Institute, Cary, NC, USA).

Biotype effects on hot and cold carcass weights, cooler shrink, adjusted preliminary yield grade, kidney-pelvic-heart fat, ribeye area, yield grade, and marbling score were analyzed using SAS PROC MIXED in SAS 9.4 (SAS Institute, Cary, NC, USA). The pdiff option in lsmeans was used to detect significant differences ($P \leq 0.05$) among biotypes. We used the SAS freq procedure to classify quality grades per steer biotype ($n = 26$).

3. Results

3.1. Weight gains

Final live weight of C2 steers was greater than that that of their C1 counterparts (449.01 ± 6.96 kg • head^{-1} vs. 372.65 ± 6.56 kg • head^{-1}; $P < 0.01$). Crossbreds in both cohorts were heavier than either JRC or MC (Table 1 and Fig. 2). We found a detectable interaction between weight and date for both cohorts ($P < 0.01$; Fig. 2). Average daily gain (kg) was not different among biotypes in C1 ($P = 0.06$), although the ADG of MC1 tended to be lower than that of JRC1 or XC1 (Fig. 2). Average daily gain was lower in C2 JRC compared to C2 MC and XC ($P < 0.01$; Figure 3).

3.2. Foraging behavior

Rarámuri Criollo and crossbred steers exhibited similar movement and spatial distribution patterns (Table 2 and Fig. 4) and could not be discriminated into detectably different groups based on their grazing behavior patterns ($P = 0.08$; Table 3). A single behavior variable, time spent close to a drinker (h × d^{-1}) was selected in the discriminant stepwise procedure.

Steers were discriminated into statistically different groups on the basis of their winter and late summer grazing behavior patterns ($P < 0.01$; Table 3). The reduced discriminant function selected in the stepwise procedure included percent pixels grazed, pixel return interval, time at water (h × d^{-1}), post sunset sinuosity, and pre-dawn distance traveled. Percent pixels grazed, that was greater in winter vs. late summer (Table 2) was the variable that weighed most heavily on the classification of steers. This linear discriminant function yielded a 0% classification error rate (Table 3).

Steers were also discriminated into significantly different groups on the basis of cohort (C1 vs C2; Table 3). Four variables were selected by the stepwise procedure. These were: selection of area within 1.6 km of water; area explored during daytime hours; pixel return interval; and area explored during pre-dawn hours. Selection of area within 1.6 km of water, which was less for C1 vs. C2, was the predictor that weighed most heavily on the classification of steers. The discriminant function correctly classified all individuals in C2 and misclassified only 11.1% of C1 steers (Table 3).

Steers (JRC and XC) and cows (JRC and AH) were discriminated into detectably different groups by biotype based on three grazing behavior variables: time spent grazing, distance traveled, and time spent close to a drinker (Table 3). The cross-validation procedure correctly classified all AH cows, and no JRC cows or steers were misclassified into the AH group. One JRC cow was misclassified into the JRC steer group, whereas almost half the JRC steers and approximately a quarter of XC steers were misclassified as belonging to either the JRC cow or other steer biotype group (Table 3).

Maximum NDVI of our study pasture explained 86% ($P = 0.02$), and 65% ($P = 0.02$) of the variation in beef production expressed as kg of live weight gain per ha of C1 and C2 steers, respectively. A change in one unit of maximum NDVI was associated with a 6.3 or 5.5 change in kilograms of live body weight of steers in C1 and C2, respectively. In general, regardless of steer biotype, pixel revisit rate tended to be higher in late summer when pasture NDVI was greener and lower in winter when nadir NDVI values were observed.

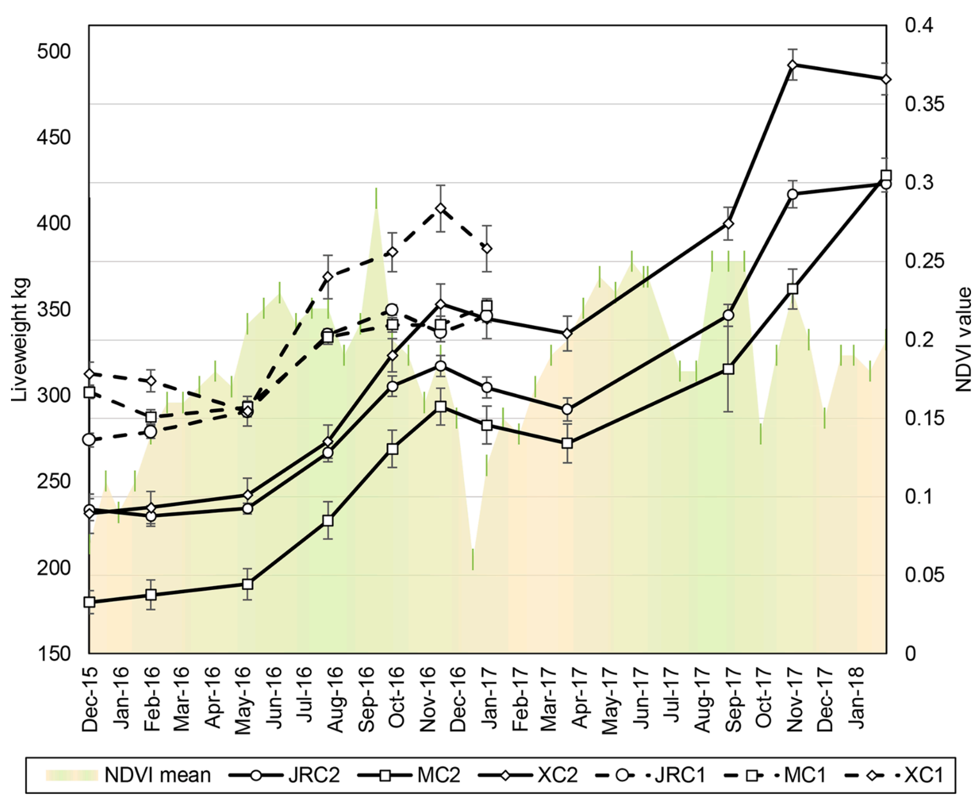

Fig. 2. Time series of animal live weights (kg) and pasture greenness (NDVI). Cohort 1 includedJornada Rarámuri Criollo (JRC1), Corriente (CO1), Waguli × Criollo (CX1) steers and Cohort 2 included Jornada Rarámuri Criollo (JRC2), Corriente (CO2), and Brangus × Criollo (CX2) steers. Means ± SE bars shown.

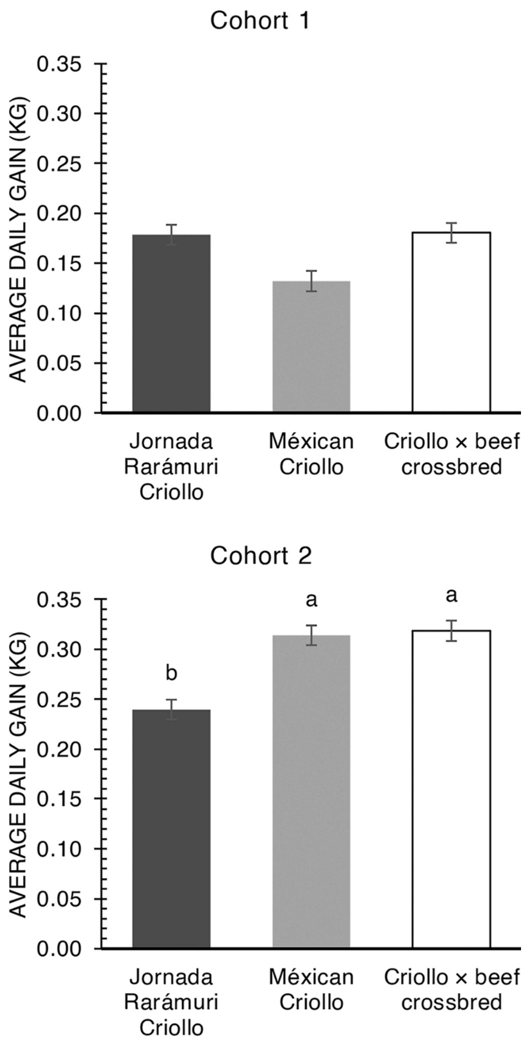

Fig. 3. Average daily gain (ADG, kg) of Jornada Rarámuri Criollo, Corriente, and Crossbred steers of both cohorts. For steers in Cohort 2, letters denote statistically significant ADG differences ($P \leq 0.05$) between treatments.

3.3. Carcass quality

Compared to XC, JRC and MC steers had lighter ($P < 0.01$) hot and cold carcass weights and higher cooler shrink values (Table 4). No differences between biotypes were observed for adjusted preliminary yield grades ($P = 0.08$), percentage of kidney-pelvic-heart fat ($P = 0.06$) or yield grade ($P = 0.07$; Table 4). Crossbred steers yielded larger ribeye areas than both JRC and MC steers, which did not differ from each other ($P < 0.01$; Table 4). Marbling scores were not different among biotypes ($P = 0.06$; Table 4). Rarámuri Criollo and XC steers tended to grade Low Choice while MC tended to grade Average Choice (Table 4). Carcass maturity (physiological age rather than chronological) was not different among biotypes which averaged overall (across biotypes) 238.1 ± 22.6 or ~ B 40 (Table 4).

4. Discussion

4.1. Weight gains

The desert grass-fed protocol used in this study achieved the goal of developing Criollo (JRC and MC) and Criollo crossbred (XC) yearling steers to slaughter weights within the 30-month target timeframe. Criollo crossbred steers were on average 27 kg heavier than JRC and MC counterparts, supporting our prediction that heavier weights were expected among XC steers because of hybrid vigor as well as the influence of improved parental beef breeds (Porto-Neto et al., 2016). Despite the difference in initial live weight of MC steers, their final weight was not different from JRC steers in either cohort suggesting that both JRC and MC steers have the potential to be grass-fed to comparable slaughter weights (Fig. 2). Steers in this study reached somewhat lighter weights than grass-finished steers of heavier breeds raised in more humid environments. Keane and Drennan (2008) finished Friesian, Angus × Friesian, and Belgian Blue × Friesian steers on Irish pasture at an average of 517 kg. Our results more closely resembled those of Orellana et al., (2009) who slaughtered Criollo Argentino at 401 kg at 30 months after being raised on extensive semi-tropical Argentinian pastures. Brahman steers finished on Australian rangeland reached finishing weights of 396 kg (Bruce et al., 2004) at 18–24 mo., which were also comparable to those observed in 30 mo. old Criollo and Criollo crossbred animals in our study.

Average daily gain of steers in cohort 1 was not different among biotypes and ADG of XC and MC steers was similar in cohort 2. Overall, mean ADG of steers in this study were similar to those reported by Reeves and Derner (2015) for yearling steers raised on shortgrass semiarid rangelands (0.6 to 1.1 kg per day). The general similarity of weight gains observed in JRC, MC and XC in this study suggests that each biotype gained weight similarly through time except for C2 JRC steers. Weight loss in both cohorts was apparent from December to March of both years. This period corresponds with the driest and thus most forage- limiting months in our system. The effect of seasonal forage limitations has been well documented by De Alba Becerra et al. (1998), Hakkila et al. (1988), Hakkila et al. (1987), King et al. (1993), and Smith et al. (1996) all of whom found strong seasonal influences on diet quality of Chihuahuan Desert rangeland-raised beef cattle that typically ingested the lowest quality diets in winter and best in summer. Live weight gain trends observed in this study are comparable to those reported by Tronstad and Teegerstrom, (2003) who tracked growth performance of Hereford steers for 20 months on Arizona rangeland and to those of Román-Trufero et al. (2019) who tracked Asturian Valley and Mountain steers on northern Spanish grass/ heathland. These authors also noted a reduction in steer weight-gains related to seasonal forage scarcity that occurs in winter and early spring (Román-Trufero et al., 2019; Sainz and Paganini, 2004; Tronstad and Teegerstrom, 2003).

Maximum pasture NDVI, our best proxy for seasonal green forage availability, explained most of the variation in beef production (kg × ha^{-1}) of steers in both cohorts. Estimates of pasture greenness (NDVI) derived from MODIS images could be used to predict short term changes in beef production in extensive desert pastures. On average, changes in one unit of NDVI were associated with a 5.9 kg change in beef produced per hectare in our research pasture. As MODIS products become more readily available to ranchers, forecasting grass-fed steer production on rangeland to plan sale/slaughter dates or supplemental feeding regimes aimed at target weight gains could become more feasible, although further research is needed to independently validate the equations derived from our study. Because MODIS-derived NDVI is a very coarse measure of green forage availability since it indicates amount/cover of photosynthetically active plant tissues of both forage and non-forage plants at a 250-m^2 resolution, there is room to greatly improve the fit of predictive equations by dissociating NDVI of forage and non-forage plant species as in Browning et al. (2018) and/or using finer resolution images.

4.2. Foraging behavior

Our findings provide support for our hypothesis that behavior and pasture use patterns of JRC and XC steers would not differ. Of 26 behavior variables tested, the only behavior selected by the stepwise procedure, albeit not statistically significant, was time spent close to a drinker. Crossbred animals tended to spend more time close to the drinker than their JRC counterparts. Our results also suggest that JRC

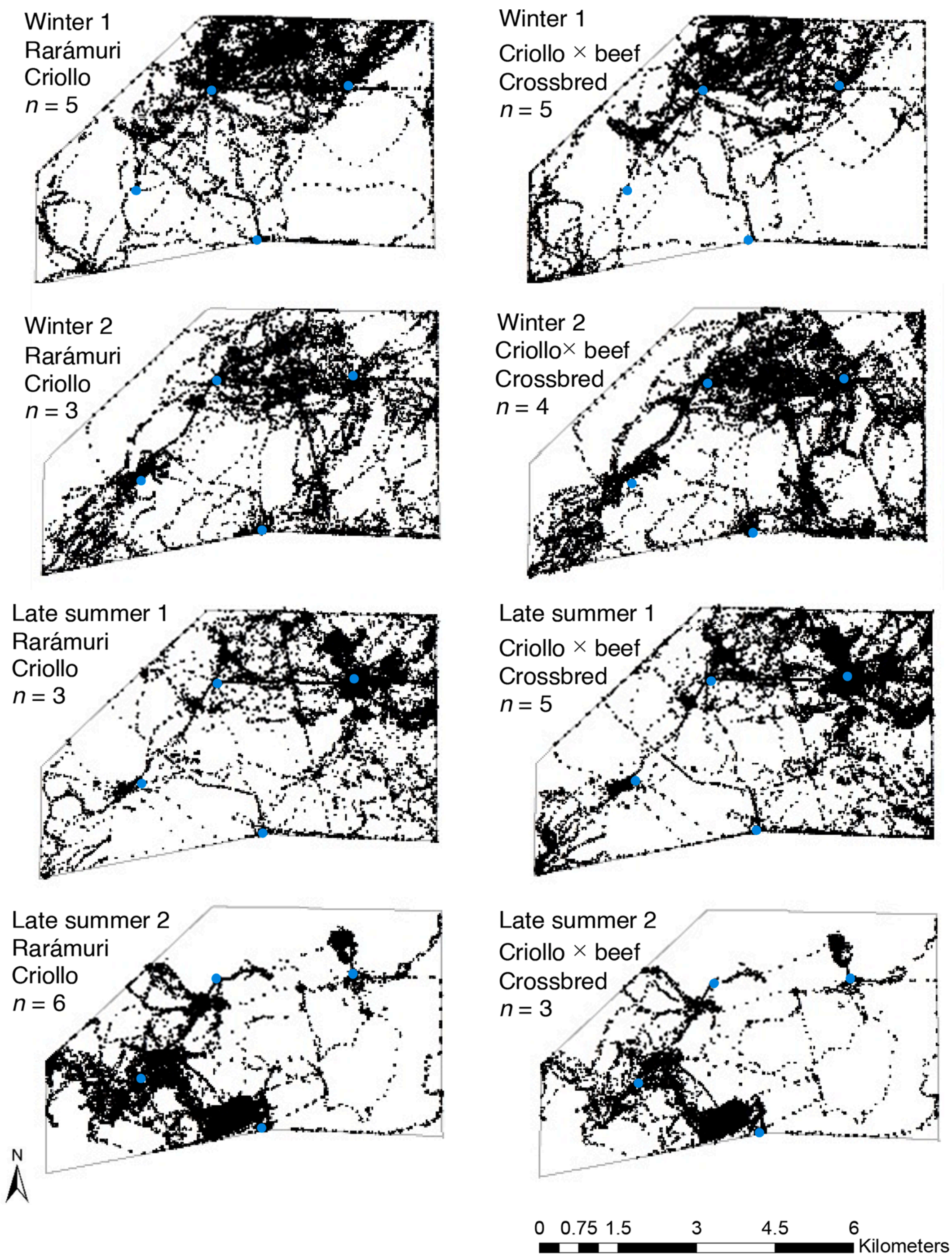

Fig. 4. Map of our study pasture at the Jornada Experimental Range showing 5-min GPS fixes of all collared Jornada Rarámuri Criollo and Criollo crossbred steers of both cohorts during Winter and Late Summer. Blue circles represent watering troughs.

cows and steers and XC steers exhibit similar grazing behavior patterns and that all three groups behaved differently than commercial beef cows. The cross-validation error rates suggested that AH cows' behavior differs from that of JRC (cows or steers) and XC animals. AH cows tended to graze for fewer hours per day, to travel shorter distances per day and to spend more time close to a drinker than either JRC (cows and steers) or XC animals. No previous studies to our knowledge, have compared foraging behavior of JRC or XC steers raised on desert rangeland to each other or to JRC and AH cows, nor have many studies compared steer to cow behavior on rangelands. Compared to JRC cows, JRC and XC steers tended to spend fewer hours grazing and less time close to a drinker each day and tended to travel greater distances per day. Therefore, developing JRC or XC steers on rangeland is likely to produce a similar or lesser environmental footprint than what is assumed for JRC cows (Peinetti et al., 2011; Spiegal et al., 2019). Behavior of steers in our study is comparable to that of heritage steers grazing mountain country in northern Spain (Román-Trufero et al., 2019). In that study, steers grazed ~8.7 h per day in summer and fall, and increased grazing time as forage became scarce (either seasonally or by year).

Steers were correctly discriminated into different groups based on seasonal changes in grazing behavior. Studies conducted with JRC cows in this (Spiegal et al., 2019) and neighboring pastures (Peinetti et al. 2011) at the Jornada Experimental Range have shown that JRC cows

Table 3
Discriminant function classification of steers into biotype season, and cohort groups, as well as cows (Spiegal et al., 2019) and steers into biotype groups, based on foraging behavior variables.

Biotype	Discriminant Function Variables:	Standardized Coefficient	Mean ± SEM Jornada Rarámuri Criollo (*n* = 17)	Criollo crossbred (*n*= 17)
	1. Time spent close to drinker (h × day^{-1})[a]	1.03	2.03 ± 0.24	2.64 ± 0.23
	Classification error rate[b]		–[c]	–
	Wilk's Lambda	0.91		
	F	3.27		
	P	0.08		
Season			Winter (*n*= 17)	Late Summer (*n*= 17)
	1. 30 m Pixels grazed (%)[d]	3.33	3.34 ± 0.09	2.20 ± 0.06
	2. 30 m Pixel return interval (days)[e]	-0.72	6.93 ± 0.09	8.14 ± 0.06
	3. Time at water (h × d^{-1})[f]	1.92	1.09 ± 0.10	0.21 ± 0.03
	4. Post-sunset path sinuosity (SI)[g]	0.79	0.60 ± 0.03	0.44 ± 0.02
	5. Pre-dawn distance traveled (km)[h]	-0.78	1.53 ± 0.14	1.59 ± 0.13
	Classification error rate		0%	0%
	Wilk's Lambda	0.03		
	F	176.92		
	P	< 0.01		
Cohort			Cohort 1 (*n*= 18)	Cohort 2 (*n*= 16)
	1. Use of area w/in 1.6 km of water (E)[i]	4.34	-0.04 ± 0.01	0.07 ± 0.01
	2. Area explored during daytime hours (ha)	1.04	190.60 ± 10.23	199.79 ± 9.66
	3. 30 m Pixel return interval (days)[j]	-1.28	8.00 ± 0.49	7.01 ± 0.24
	4. Area explored during predawn hours (ha)[k]	0.79	19.31 ± 1.64	40.84 ± 5.91
	Classification error rate[l]		11.10%	0%
	Wilk's Lambda	0.009		
	F	34.22		
	P	< 0.01		

Cows and steers			Angus Cows (*n*=18)	JRC Cows (*n*=12)	JRC Steers (*n*= 17)	XC Steers (*n*= 17)
	1. Time grazing (h × day^{-1})		7.87 ± 0.47	9.66 ± 0.36	8.56 ± 0.52	7.79 ± 0.40
	2. Distance traveled (km × day^{-1})		6.13 ± 0.12	8.50 ± 0.30	10.05 ± 0.28	9.86 ± 0.40
	3. Time spent close to drinker (h × day^{-1})[m]		8.01 ± 0.24	3.88 ± 0.31	2.03 ± 0.24	2.64 ± 0.23
	Cross-validation Classification:					
	Angus Cows		18	0	0	0
	RC Cows		0	10	2	0
	RC Steers		0	1	9	7
	XC Steers		0	0	5	12
	Classification error rates		0	16.7	47.1	23.4
	Wilk's Lambda	0.059				
	F	34.46				
	P	< 0.01				

[a] Time spent within 200 m of the drinker.
[b] Classification error rates were calculated using cross-validation analyses.
[c] Since the DA was unable to discriminate steers into detectably different groups on the basis of breed (*P* = 0.08), classification error rates were not computed.
[d] Calculated with the first 20 days of GPS data.
[e] Time within 15 of the drinker.
[f] Sinuosity Index (0= most sinuous; 1 = straight path).
[g] Distance traveled between midnight and dawn.
[h] Classification error rates were calculated using cross-validation analyses.
[i] Ivlev's electivity index *E* where -1 = avoidance; 0 = indifference; and 1 = selection.
[j] Calculated with the first 20 days of GPS data.
[k] Area explored between midnight and dawn.
[l] Classification error rates were calculated using cross-validation analyses.
[m] Time spent within 200 m of drinkers.

behave differently during dormant and growing seasons apparently responding to changes in forage availability (Peinetti et al. 2011) or plant phenology (Spiegal et al., 2019). Peinetti et al. (2011) found that spatial distribution of JRC varied seasonally, expanding dramatically during the dormant season whereas Spiegal et al. (2019) reported similar patterns when comparing spatial distribution of JRC cows in the pasture where we conducted our study during green-up and dry-down vegetation phases of the 2008 growing season. Steers in this study, both JRC and XC, grazed larger areas, and traveled further, following straighter paths after sunset hours during winter (dormant season) vs. late summer (growing season). We speculate that steers were possibly engaging in concentrated searches for high quality forage during late summer (i.e. increased path sinuosity) as previously documented in desert beef cattle (Russell et al., 2012) and bison (Fortin, 2003). Steers revisited pixels less frequently in winter than in late summer presumably in response to forage availability and spent more time at water during winter than late summer presumably because of seasonal dryness and corresponding reductions in water intake from forage and/or ephemeral ponding sources. Sawalhah (2014) also documented that rangeland beef cows tend to graze pasture pixels more frequently during green-up than during plant dormancy. Steers visited a majority of 30 m^2 pixels only once. This pasture use pattern closely corresponds to reports by Roach (1950) who suggested that "cattle grazing freely with ample forage available, as a rule, graze a clump once and then move on to a fresh clump … [and] will not return to a grazed plant unless forage is short or until grass has put out new succulent growth" (p. 182). Light stocking

Table 4
Carcass characteristics of 30-month Jornada Rarámuri Criollo (JRC), Mexican Criollo (MC), and Criollo x Brangus crossbreds (XC) belonging to Cohort 2.

	Mean and SEM			P-value
	JRC[1]	MC[2]	XC[3]	type three fixed effects
Hot carcass weight (kg)	220.49[b] ± 6.42	216.36[b] ± 6.87	265.18[a] ± 6.43	< 0.01
Cold carcass weight (kg)	210.18[b] ± 5.36	206.19[b] ± 6.71	254.30[a] ± 6.28	< 0.01
Cooler shrink (%)	0.049[b] ± 0.00	0.049[b] ± 0.00	0.043[a] ± 0.00	0.04
Adjusted preliminary yield grade	2.30 ± 0.05	2.46 ± 0.06	2.44 ± 0.06	0.08
% kidney-pelvic-heart fat	1.86 ± 0.15	2.43 ± 0.18	1.94 ± 0.17	0.06
Ribeye area (cm^2)	57.17[b] ± 1.39	54.29[b] ± 1.74	61.68[a] ± 1.66	< 0.01
Yield grade	1.65 ± 0.09	1.99 ± 0.11	1.71 ± 0.10	0.07
Marbling score[4]	451.82 ± 30.76	565.71 ± 38.55	456.25 ± 36.06	0.06
Maturity[5]	244.55 ± 6.64	241.43 ± 8.32	226.25 ± 7.78	0.20

Biotype		Quality Grade					
		Standard +	Choice -	Choice 0	Choice +	Prime -	Total
MC[2]	Frequency	4	1	0	1	1	7
	Percent	15.38	3.85	0	3.85	3.85	26.92
	Row %	57.14	14.29	0	14.29	14.29	
	Column %	26.67	12.5	0	100	100	
JRC[1]	Frequency	7	3	1	0	0	11
	Percent	26.92	11.54	3.85	0	0	42.31
	Row %	63.64	27.27	9.09	0	0	
	Column %	46.67	37.5	100	0	0	
XC[3]	Frequency	4	4	0	0	0	8
	Percent	15.38	15.38	0	0	0	30.77
	Row %	50	50	0	0	0	
	Column %	26.67	50	0	0	0	
Total	Frequency	15	8	1	1	1	26
	Percent	57.69	30.77	3.85	3.85	3.85	100

[1] JRC: Jornada Rarámuri Criollo
[2] MC: Mexican Criollo
[3] Criollo × beef crossbred. In cohort 2, these were Criollo × Brangus steers.
[4] Marbling Score Code: 100-199: practically devoid; 200-299: traces; 300-399: slight; 400-499: small; 500-599: modest; 600-699: moderate; 700-799: slightly abundant; 800-899: moderately abundant; 900- or greater: abundant.
[5] Overall Maturity of all steers was classified as "B".
[a,b] Means with same letters are the same. Means with different letters are different. Means with no letter are not different.

rates used in this study may have offered more and better-quality forage resulting in more live weight gain as has been described elsewhere in the Chihuahuan Desert (Thomas et al., 2015). The 'graze a clump, move on, and don't return until new growth emerges' phenomenon presented by Roach (1950) that we observed in both seasons at a 30 m^2 'pixel' scale suggests that JRC steers with adequate forage are unlikely to return to a previously grazed patch, except to access a drinker, and could also imply that JRC and XC perhaps create fewer hotspots of intense use compared to other breeds as was reported for JRC cows by Spiegal et al. (2019).

Steers in C1 and C2 were classified into significantly different groups based on their grazing behavior. Cohort 1 steers tended to avoid areas within 1.6 km of water, appeared to explore larger areas (ha) during daytime and pre-dawn hours, and tended to return to pixels more frequently than their C2 counterparts. The first cohort was exposed to considerably drier conditions with less green forage during late summer. Sawalhah et al. (2016) observed that rangeland beef cows can expand their daily area (24 h) in forage-scarce years up to double that of cows in years of forage surplus. Our results also agree with Díaz Falú et al. (2014) who report year-to-year differences in area explored by GPS-collared cattle in response to preferred available forage. These differences in foraging behavior perhaps also explain why steers in C1 weighed significantly less at slaughter than those in C2.

4.3. Carcass quality

We found no major differences in carcass quality parameters of C2 JRC, MC, or XC steers developed on Chihuahuan Desert rangeland. However, as with live weight, carcass weight of XC steers was greater than that of their JRC and MC counterparts. In a similar study to ours, Criollo Argentino and Hereford × Criollo Argentino developed on grass in La Pampa, Argentina to 26 or 32 months exhibited similar dressing percentages per bioptype (Criollo Argentino: 57.2%; vs Hereford × Criollo Argentino: 56.9%; Garriz et al., 2008). A preliminary analysis that evaluated JRC and XC steers developed on rangeland revealed similar mature weights to our animals, wherein JRC finished between 363 – 454 kg and XC at 454 – 544 kg (Anderson et al., 2015). This preliminary analysis also indicated that JRC and XC steers had similar Warner-Bratzler shear force values. Both biotypes produced striploin steaks with very tender meat profiles (Anderson et al., 2015). A study comparing fatty acid composition of Criollo Argentino to Braford steers raised on semi-tropical rangeland found more unsaturated and less saturated fatty acids in Criollo Argentino than their beef breed counterparts (Orellana et al., 2009). Compared to Criollo Argentino reported by Orellana et al., (2009), however, our steers all had much smaller ribeye areas and lower marbling scores, which we expect is related to diet quality and maturity rather than genetics, because these metrics were constant regardless of biotype. Uruguayan Hereford steers finished on grass also yielded similar ribeye areas to ours (~63 cm^2; Realini et al., 2004). Compared to conventionally finished Angus-cross cattle with A maturity levels reported by Dunn et al. (2000), our carcass weights, and kidney-pelvic-heart fat % were similar, though our animals yielded slightly smaller ribeyes, and graded lower in marbling score and quality grade, likely due to advanced carcass maturities which among our steers were all considered B's (As maturity advances the criterion for quality grade becomes stricter; see Holland and Loveday (2013) for more detailed discussion; Table 4). The carcass quality of steers in our study can be considered typical in comparison to grass-finished beef overall; US grass fed beef is often graded USDA Select or lower (Cheung and McMahon, 2017). However, emerging evidence suggests that Criollo carcasses may not easily fit within the traditional meat grading system, as they tend to deposit limited amounts of subcutaneous fat compared to beef counterparts, but still produce desirable flavor and tenderness, though this requires more detailed study (Armstrong et al., 2019).

4.4. Management implications

Our results suggest that it is possible to develop yearling Rarámuri Criollo, Mexican Criollo or Criollo crossbred steers to reach slaughter weights at 30 months using light stocking rates and supplementing with grass hay during the last month on hot desert rangeland. Criollo crossbred steers grew to greater live weights than either Rarámuri Criollo or Mexican Criollo steers finished on Chihuahuan Desert rangeland. Rarámuri Criollo and Criollo crossbred steers appear to exhibit the same desirable foraging behavior patterns reported previously in Rarámuri Criollo cows. Satellite-derived estimates of vegetation greenness could be used as a tool to predict beef production in kg $\times$ ha^{-1}. Our results suggest that crossbreeding and/or grass-fed steer development programs could be implemented by ranchers raising Rarámuri Criollo cattle to overcome the lack of market for weaned calves and provide quality beef for niche markets.

Author contributions

MM: conducted study, data analysis, writing; **AC**: conceptualization, methodology, supervision, writing & review editing; RE: conceptualization, methodology, supervision, writing & review editing, funding; **SN**: helped conduct study, review editing; **AG** conceptualization, supervised field study, provided resources; **QG** and **HC** developed software for analysis; **SS** writing and review editing; **SSN**: conceptualization, methodology and writing and review editing; **AB**: conducted meat analyses and contributed to writing and review editing.

Declaration of Competing Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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