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RESEARCH ARTICLE

Integrating space and time: a case for phenological context in grazing studies and management

Dawn M. BROWNING (✉)[1], Sheri SPIEGAL[1], Richard E. ESTELL[1], Andres F. CIBILS[2], Raul H. PEINETTI[3]

1 USDA-Agriculture Research Service, New Mexico State University, Las Cruces, NM 88003, USA
2 Department of Animal and Range Sciences, New Mexico State University, Las Cruces, NM 88003, USA
3 Facultad de Agronomía, Universidad Nacional de La Pampa, Santa Rosa, La Pampa, CP 6300, Argentina

Abstract In water-limited landscapes, patterns in primary production are highly variable across space and time. Livestock grazing is a common agricultural practice worldwide and a concern is localized overuse of specific pasture resources that can exacerbate grass losses and soil erosion. On a research ranch in New Mexico with average annual rainfall of 217 mm, we demonstrate with a quantitative approach that annual seasons vary greatly and examine foraging patterns in Angus-Hereford (*Bos taurus*) cows. We define five seasonal stages based on MODIS NDVI: pre-greenup, greenup, peak green, drydown and dormant, and examine livestock movements in 2008. Daily distance traveled by cows was greater and foraging area expanded during periods with higher precipitation. A regression model including minimum NDVI, rainfall and their interaction explained 81% of the seasonal variation in distance traveled by cows ($P < 0.01$). Cows explored about 81 $ha \cdot d^{-1}$ while foraging, but tended to explore smaller areas as the pasture became greener (greenup and peak green stages). Cows foraged an average of 9.7 h daily and spent more time foraging with more concentrated search patterns as pastures became greener. Our findings suggest that phenological context can expand the capacity to compare and integrate findings, and facilitate meta-analyses of grazing studies conducted at different locations and times of year.

Keywords GPS collars, Jornada Experimental Range, land-surface phenology, livestock movement, LTAR, MODIS NDVI, rangeland

1 Introduction

In arid or water-limited landscapes (arid lands), "average" conditions are difficult to define. Many arid lands are characterized by high spatial heterogeneity and temporal variability in precipitation[1] that together yield highly variable patterns in primary production in space and time[2,3]. Spatial heterogeneity in land-surface conditions and primary productivity and temporal variability in precipitation are important to pastoral communities[4] and other land management decision-makers. Spatiotemporal variability in forage resources largely explains regional livestock migration routes in areas where nomadic pastoralism is practiced[5] and is the driver of basic rangeland management practices in largely sedentary pastoral ranching enterprises of western North America[6]. Tools to assist planning and management in these systems are needed.

Remote-sensing tools are a recognized means to characterize land-surface condition across broad areas and over time[7]. Techniques that leverage the capabilities of long time series from remote-sensing platforms and long-term ground observations are especially helpful[8,9]. The Normalized Difference Vegetation Index (NDVI)[10] is a commonly used metric in remote-sensing studies that involve mapping or monitoring green or photosynthetically active vegetation. NDVI has also been combined with GPS data to monitor animal movements, determined habitat use and evaluate grazing preferences[11–14]. As one example of this integrated spatial approach to livestock behavior, Handcock et al.[14] recorded movements of livestock over a 3-d period to demonstrate that cows tracked changes in NDVI. We propose that growing season stages can offer insight and ancillary information for interpretation and planning of livestock grazing studies.

Rangelands are defined as landscapes on which the natural vegetation is dominated by grasses, forbs and shrubs, and that are managed as natural ecosystems[15]. Plant functional groups that occur on rangelands (e.g., C_4 and C_3 grasses and forbs, and C_3 shrubs) have distinct phenological or life cycle patterns that reflect differences in growing season stages such as greenup and drydown[16,17].

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Correspondence: dawn.browning@ars.usda.gov

Field data and local knowledge portray phenological differences, but it remains unclear whether phenological signals for grass versus shrub vegetation can be distinguished via satellite remote sensing. In the case of cattle, the most prevalent livestock produced on rangelands of the USA, increases in shrub cover typically decrease forage availability and quality, as cattle tend to prefer grasses[18]. Thus, the ability to depict the shrub signal via remote sensing would be useful for studies related to grazing management and their implications for profitability of agricultural production.

In temperate rangelands in the USA, rotating livestock among pastures is a typical strategy for reducing impacts to particular rangeland resources and matching livestock with forage resources; however, for the arid Southwest, there is little evidence that high-frequency rotations among pastures improves production or environmental quality[19]. Therefore, continuous grazing of large pastures on arid rangelands in the USA is typical. However, in many arid lands, a primary concern about continuous livestock grazing is localized overuse of specific pasture resources, because this behavior can exacerbate perennial grass losses and soil erosion. Accordingly, efforts are commonly made to enhance the distribution of livestock in arid pastures to avoid these deleterious effects[20]. Within pastures, typical approaches to improving distribution of livestock include strategic placement of watering points, salt and mineral licks, and shade structures[21]. Although rangeland managers have used attractants to lure livestock away from water for over a century[22], sharp seasonal and interannual variation in primary production frequently render attractants ineffective[23]. The ability to monitor rangeland phenological dynamics in near real-time would allow a more effective use of attractants to enhance or expand distribution away from watering points and toward forage of desired phenological stage, and would inform decisions about attractant placement in extensive grazing pastures.

Depending on objectives, grazing studies can be conducted over long or short time scales — focused on intra-annual or inter-annual movement patterns, resource selection, and/or outcomes related to environmental effects or potential profitability[18–20]. Given high inter-annual variability in primary production (i.e., forage production), we anticipate that integrating seasonal patterns of productivity and information regarding climatological context (e.g., precipitation) will enhance the ability to compare results among studies conducted at different times and locations. Doing so may help resolve unexplained variance when examining results in the context of other grazing studies. We contend that the effects of differences between years and/or between studies can be better understood by incorporating the phenological context or stage of growing season for grazing studies.

We examined patterns in foraging use for Angus-Hereford (AH, *Bos taurus*) crossbred cows on a long-term research ranch in arid southern New Mexico to illustrate the importance of spatial and temporal patterns in land-surface phenology. We also explored whether imagery from the moderate resolution imaging spectroradiometer (MODIS) sensor provides seasonal metrics across space and time that could inform resource placement. We explored whether and to what extent foraging patterns of AH cows mirror patterns in vegetation greenness depicted via satellite, and whether foraging patterns change across seasonal stages defined via land-surface phenology. We sought to evaluate the utility of MODIS NDVI as a tool to improve comparability of grazing studies conducted in different years and as a tool to help managers better predict the optimal location of attractants for improved cattle distribution.

Specifically, our objectives were to: (1) derive growing season metrics to distinguish seasonal stages using 250-m MODIS NDVI between 2003 and 2009 at the pasture scale and separately for grass- and shrub-dominated areas, (2) examine whether annual seasonal profiles for grass- and shrub-dominated areas differed over the seven years, and (3) evaluate the hypothesis that livestock foraging activity (i.e., spatial patterns) tracks landscape greenness and assess whether livestock movement patterns are linked with greenness change throughout the stages of the 2008 growing season.

2 Materials and methods

2.1 Study site

The study was conducted at the Jornada Experimental Range (JER) in southern New Mexico in the northern Chihuahuan Desert. The JER is situated between the Rio Grande corridor and the San Andres Mountains within the southern Jornada del Muerto Basin in the Southern Desertic Basins, Plains, and Mountains Major Land Resource Area[24] (Fig. 1). Soils at the JER are dominantly sandy with variable surface sand content, soil depth and subsurface clay accumulations[25].

The Chihuahuan Desert is spatially heterogeneous with soils and vegetation varying together over short distances. Ecological site classification has become a useful tool for organizing such spatial heterogeneity. Ecological sites are recurring divisions of land that differ in their soil and physical characteristics, potential vegetation, and response to disturbance and management actions[24]. Recently, ecological sites have been mapped on Chihuahuan Desert landscapes[26], and the maps are useful for various stakeholders — researchers, ranchers, land managers — to conceptualize the landscape and cattle use of the landscape in a common framework.

Long-term (1918–2009) average annual rainfall is 217 mm and about 53% of this falls from July to September as monsoonal storms originating from the Gulfs of Mexico and California. Mean maximum monthly

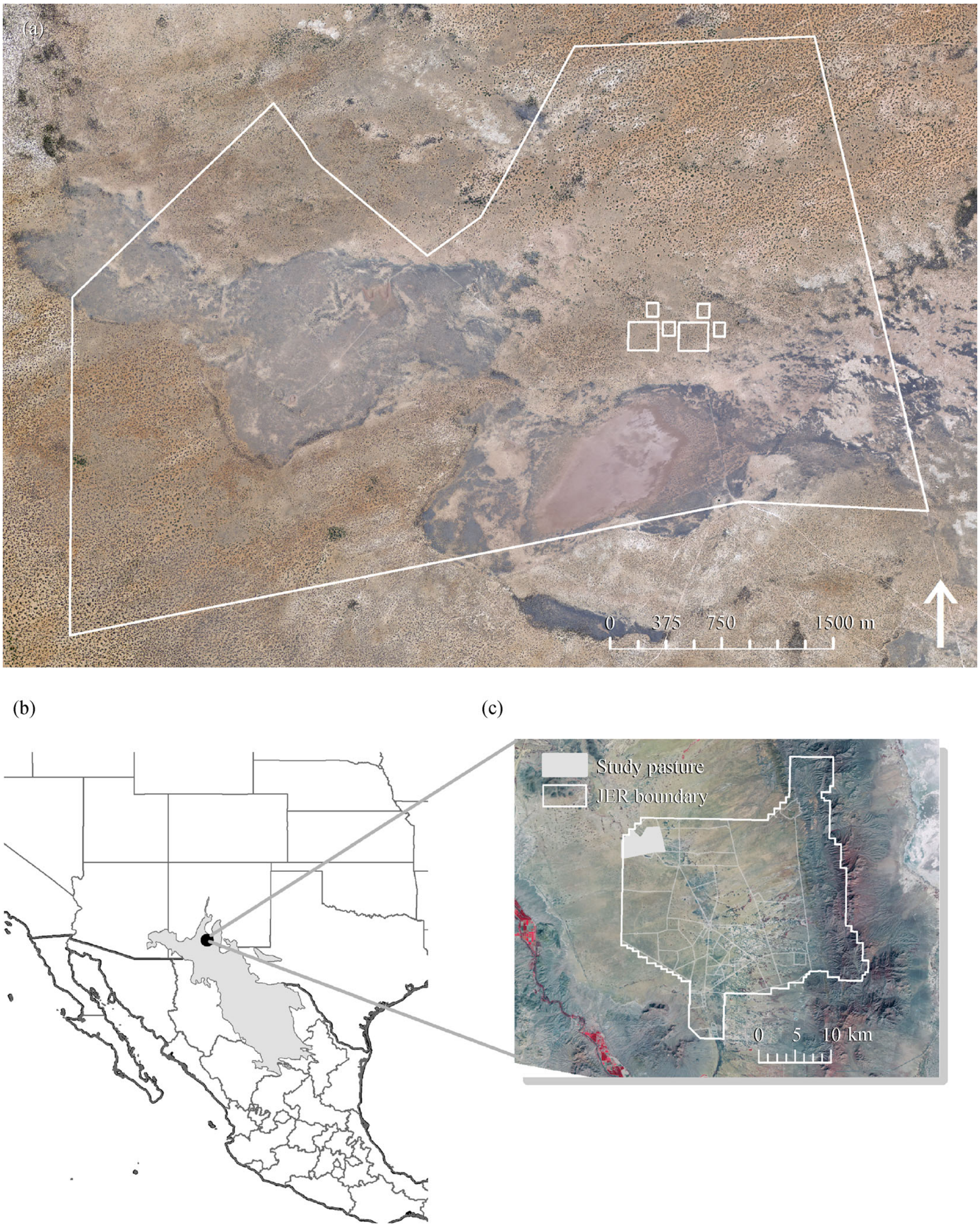

Fig. 1 The 1525-ha study pasture (white outline in panel a) atop a 1.0-m natural color composite aerial photo mosaic acquired June 2011 as part of the National Agriculture Imagery Program by the USDA on the JER in the northern Chihuahuan Desert (gray area in panel b). The study pasture occurs in the north-west corner of the 780-km^2 JER (white outline in panel c) shown on a Landsat satellite image acquired November 17, 2009. JER pasture boundaries in panel c are depicted in light gray.

temperatures range from 13.5°C in January to 35.0°C in July[27]. Longer-term drought-pluvial cycles are evident in records of annual precipitation and are largely driven by teleconnection patterns arising from the El Nino-Southern Oscillation (ENSO)[28]. The prominent period of drought from 2000 to 2003 related to ENSO variability at the JER represents the broader pattern of drought during this period throughout much of the western USA[29]. Record-breaking rainfall occurred during 2006 and 2008 monsoons (Fig. 2).

The livestock movement study was conducted June through December 2008 on a 1525-ha pasture with central coordinates 32.718° N, 106.84° W (Fig. 1). Biophysical heterogeneity in the study pasture is high as is represented

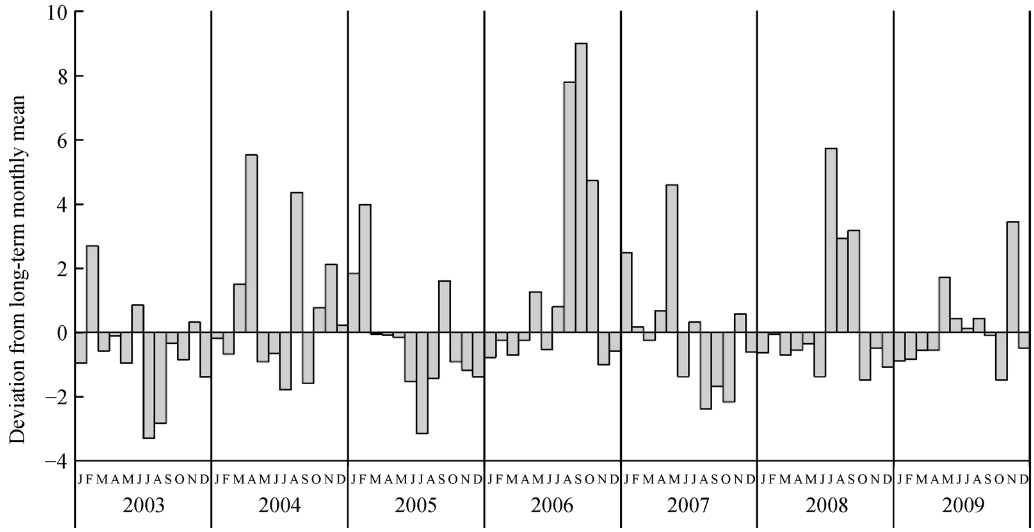

Fig. 2 Standardized difference from long-term (1918 to 2009) monthly mean rainfall on the study pasture on the Jornada Experimental Range. Standardized difference is the individual monthly value minus long-term monthly average divided by the monthly standard deviation.

by the diversity of mapped ecological sites[26]: Sandy, Clayey, Loamy, Deep Sand, and Gypsiferous Playa. In this pasture, the Clayey ecological site (R042XB023NM) is dominated by the C_4 perennial tobosa grass (*Pleuraphis mutica*). In contrast, the Deep Sand ecological site (R042XB011NM) is dominated by the C_3 shrub honey mesquite (*Prosopis glandulosa*) that may also include mesa dropseed (*Sporobolus flexuosus*) in shrub interspaces. The Loamy ecological site (R042XY014NM) includes a mix of the C_4 grasses *P. mutica* and *S. flexuosus,* along with the C_3 shrubs *P. glandulosa* and broom snakeweed (*Gutierrezia sarothrae*). The Sandy ecological site (R042XB012NM) is dominated by *P. glandulosa* and four-wing saltbush (*Atriplex canescens*) shrubs along with dropseed grasses (*Sporobolus* spp.) and black grama (*Bouteloua eriopoda*). The Gypsiferous Playa ecological site is a provisional class and notably different from other ecological sites due to its higher proportion of bare ground, and annual and biennial forbs. Seven artificial watering points were provided for the livestock during the study. Five were dirt tanks that fill with water with sufficient rainfall. The other two were permanent drinkers fed by pipeline and well.

2.2 Livestock GPS collar data

Cattle movement and activity were monitored for four sampling periods (treated as separate trials) between June and December 2008 (Table 1). At the start of each sampling period, mature AH cows without calves were fitted with Lotek GPS collars (Model 2000 and 3000, Lotek Wireless Inc. Newmarket, ON, Canada) programmed to acquire geographic locations at 5-min intervals, and then turned out into the pasture with no intervention until gathering. Sampling events ranged from 9 to 18 d and included 9 to 15 cows. A subset of the cows was collared in each period, ranging in number from 5 to 10 (Table 1). Stocking density was 102 to 171 ha per animal, depending on the number of cows in the pasture during the sampling period. The cows were about 4 years old with an average weight of 474 kg, and had experience grazing in the vegetation and conditions of the JER.

To prepare the GPS data for analysis, we omitted collar data sets with a high proportion of fixes logged without dates or geographic location information. We excluded the days that animals were introduced and removed from the pasture to remove anomalies in animal behavior in the corrals[30]. To facilitate comparison of locations across sampling periods, we only report results of the GPS fixed locations for day 2 to day 7 for each period. We also focus only on movements assumed to correspond with foraging, which we calculated based on rate of movement following published methods[31] and described below. Number of cows monitored per period ranged between 5 and 10 depending on GPS collar failure rates (Table 1).

2.3 Livestock activity metrics

Daily activity of individual cows fitted with GPS collars was described by calculating distance traveled (km), area of the pasture covered while foraging (foraging area, ha), time allocated to grazing (h), and search pattern or the daily distance traveled/daily foraging area. The spatial pattern metric expressed as distance traveled per area covered in a day is an indirect measure of

Table 1 Sample periods for AH cows and seasonal stages during the 2008 study and dates of NDVI images selected to represent land-surface conditions for each trial. The seasonal stages are defined in Section 2.5

Sample date	No. of cows	No. of GPS collars	Seasonal stage	NDVI image date
Jun. 12–17	11	8	Pre-greenup	Jun. 15
Jul. 4–9	9	6	Greenup	Jul. 17
Aug. 30–Sep. 4	10	5	Eak green*	Sep. 3
Nov. 6–11	11	10	Drydown	Nov. 6

Note: *The third sample period occurred during the transition from greenup to peak green. For our analysis, we classify the third period as peak green.

movement path sinuosity or serpentine movement patterns that we categorize as foraging[32]. Animal foraging was distinguished from other behavioral classes using criteria developed by Peinetti et al. 2011[31]. Movements of 5-m or less during a 5-min time interval were assumed to correspond to resting (<1 m·min^{-1}). Movements of 100-m or more during a 5-min time interval were assumed to correspond to walking (20 m·min^{-1}). Movements$\geqslant$ 1 m·min^{-1} and$\leqslant$20 m·min^{-1} were assumed to correspond with foraging; thresholds were based on existing research[30,31,33]. Number of cows monitored per period ranged between 5 and 10 depending on GPS collar failure rates (Table 1).

2.4 Satellite depictions of greenness with time-series NDVI

Patterns in land-surface phenology were derived using time-series NDVI from MODIS pixels covering the study pasture. We acquired all 250-m resolution MODIS NDVI images (MOD13Q1 data product, 16-d resolution) from 2003 to 2009, totaling 160 scenes (H09V05) and subset the pixels intersecting the pasture boundary (Fig. 3).

We chose NDVI as the remote-sensing metric for two reasons despite its limitations in arid environments due to effects of exposed soil, standing dead vegetation and litter on the spectral response[34,35]. First, it is widely used as a relative and indirect indicator of the amount of photosynthetic biomass[10] and second, recent research at the JER indicated that MODIS NDVI was more strongly correlated to biomass measurements than Landsat satellite NDVI due to a higher temporal resolution and a cleaner temporal signal (i.e., fewer artifacts and data gaps)[36].

2.5 Growing season metrics and seasonal stages

We summarized NDVI pixel values in two ways for our analyses: at the pasture-level to link with livestock movements and at ecological site-level described in the next section. For the pasture-level analysis, we averaged all MODIS pixel values to represent pasture-scale NDVI. We calculated growing season metrics using TIMESAT software[37] because of its widespread utility and ease of implementation. TIMESAT smoothes the NDVI data and fits the smoothed data to the selected function. The pasture-level mean NDVI was analyzed using the Savitzky-Golay filter to fit the NDVI curve and we applied a 0.15 seasonal amplitude threshold to derive four growing season metrics; start of season (SOS), end of season (EOS), growing season length (GSL) and base NDVI. Peak NDVI and date of peak were manually extracted as the maximum NDVI value (and date of maximum) for each year. The 0.15 seasonal amplitude filter was selected based on prior experience with MODIS at the JER[16].

We defined five seasonal stages based on land-surface phenology from greenness indices resulting from time-series imagery. Greenup represents the period from SOS to the start of the peak green period. The peak green period is either an asymptote in the time series at the maximum vegetation index value or the period defined by the image sample interval (in the case of MODIS, 16 d) on either side of the peak greenness value. We defined peak season using the latter method as the 32-d period centered on the date of peak NDVI. Drydown is the period following peak green to the EOS date. Dormant represents the days following EOS to the end of the year. Botanically speaking, dormancy — or the period of no photosynthetic activity — extends into the following calendar year and growing season. This period of plant inactivity beginning from January 1 can be called the pre-greenup or the dormant stage.

From the standpoint of cattle research and management, nutritional quality of forage species declines with plant maturity and is therefore expected to track seasonal forage greenness dynamics closely (i.e., highest during greenup and lowest during dormancy)[38]. Pastures with photosynthetically active plants are likely to offer better nutrition for cattle than dormant pastures; thus, it may be assumed that overall forage quality is higher during greenup and peak green than during pre-greenup, drydown or dormant stages.

2.6 Phenological profiles — grass and shrub curves

To characterize seasonal NDVI profiles for grass- and shrub-dominated areas and examine whether they differ, we stratified the study pasture using two data sets; (1) a fine-scale classification of shrub cover and (2) a map of ecological sites. Honey mesquite patches were classified using a four-band Quickbird satellite image acquired August 22, 2008 that was subsequently resampled to 1-m

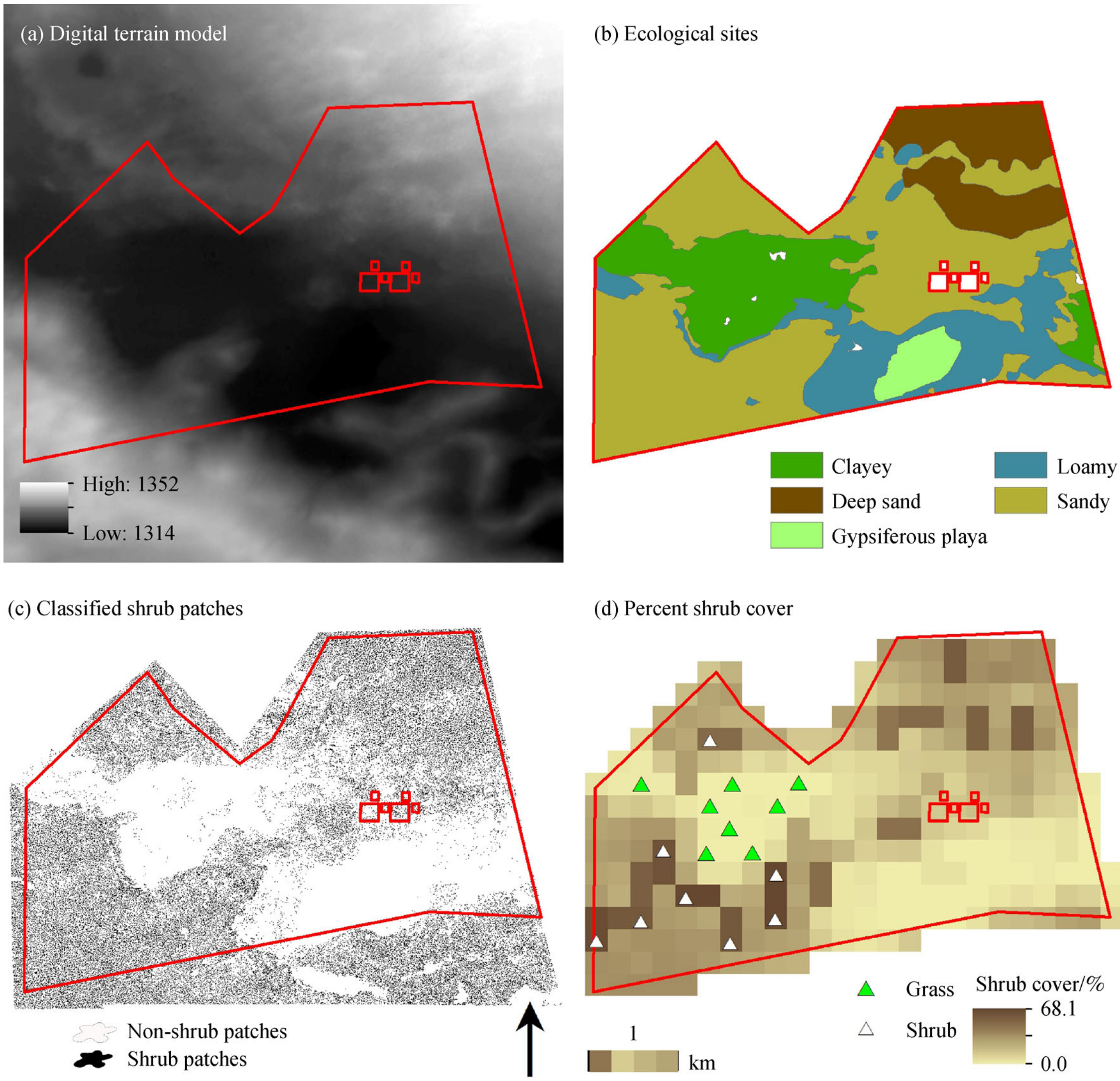

Fig. 3 Topographic and biophysical attributes of the study pasture on JER (red polygon). Digital terrain model (a) indicates that elevation ranges from 1352 to 1314 m. Five ecological sites (b) occur in the 1527-ha study pasture. Panel c depicts classified shrub cover derived from 1.0-m Quickbird satellite imagery that was convolved to 250-m pixels (d). Eight MODIS pixels were selected within the two dominant ecological sites (Sandy and Clayey) to represent shrub- (white triangles) and grass-dominated (green triangles) land-surface phenology. Red boxes in the pasture represent long-term study exclosures.

resolution. The image classification was performed using Feature Analyst™ Software (Overwatch Textron Systems, Providence, RI, USA) in ArcGIS (ESRI, Redlands, CA, USA) and is fully described in Peinetti et al.[31]. The mesquite image classification was convolved to depict mesquite shrub cover within the 250-m MODIS pixels (Fig. 3d).

In addition, we used a map of ecological sites[26] to guide selection of pixels to represent grass- and shrub-dominated areas. We sought to capture the high and low ends of the shrub cover gradient within Clayey and Sandy ecological sites (Fig. 3b), which corresponded to non-shrub and shrub-dominated areas, respectively. We achieved this by identifying the eight pixels with the highest shrub cover (in the Sandy ecological site) and the eight pixels with the lowest shrub cover (in the Clayey ecological site; Fig. 3). After selecting the grass- and shrub-dominated pixels, we sampled time-series NDVI values and calculated the average for the two sets of pixels. Mean shrub cover for grass-dominated pixels corresponding to Clayey ecological site was 0.4% while mean shrub cover was 54.7% on the Sandy ecological site.

To examine whether seasonal profiles for grass- and shrub-dominated areas exhibit significant differences during 2003 to 2009, we compared annual NDVI time series using Kolmogorov–Smirnov (K-S) tests. The null hypothesis was that annual distributions for grass and shrub NDVI do not differ.

2.7 Cattle movement patterns by growing season stage

We used three analyses to evaluate the hypothesis that spatial foraging patterns change throughout the growing season. We anticipated that spatial search pattern of cows (daily distance traveled/daily foraging area) becomes more concentrated as pasture greenup progresses. We conducted linear correlation analyses in SAS 9.3 (SAS Institute, Cary, NC, USA) using the PROC CORR procedure to explore pairwise relationships between cattle activity parameters (on a per-cow basis) and measures of pasture NDVI as well as rainfall during each of the four seasonal periods studied. Response variables were average daily distance traveled (km), average daily foraging area (ha), search pattern (daily distance traveled/daily foraging area), and average daily time spent grazing (h). Predictor variables were average NDVI for the entire pasture, minimum and maximum pixel NDVI, NDVI standard deviation, and rainfall for each seasonal stage.

Secondly, we conducted multiple regression analyses in SAS 9.3 using the PROC GLM procedure to determine whether seasonal variation in cattle activity patterns could be explained by changes in NDVI and weekly rainfall. A probability value of $P \leqslant 0.05$ was used to declare statistical significance in all tests. All data were examined prior to analysis to screen for nonlinearities and possible violations of linear model assumptions.

Thirdly, we explored patterns in NDVI by growing season stage comparing locations where cows were and were not present at each seasonal stage. This comparison across seasons offers a coarse-resolution (i.e., using MODIS NDVI 250-m pixels) perspective on greenness patterns where cows did and did not forage; it is not an attempt to model foraging behavior or resource selection. To achieve this, we generated a foraging density layer as the count of forage locations in each 250-m MODIS pixel. We randomly selected 15 pixels each from the portions the pasture classified as grazed and ungrazed for each trial avoiding water sources, and conducted *t*-tests to determine whether NDVI of grazed versus ungrazed pixels differed. Tests of homogeneity of variance were conducted prior to analysis and a probability value of $P \leqslant 0.05$ was used to declare statistical significance.

3 Results

3.1 Land-surface phenology patterns at the pasture-scale

Patterns in vegetation greenness were muted in 2003, 2004 and 2005; amplitudes in NDVI were less than 0.06 (Table 2; Fig. 4). As such, growing season lengths determined using the seasonal amplitude threshold in Timesat for the first 3 years are over-estimated with a mean of 294 d compared to mean growing season length in 2006 to 2009 of 197 d. Mean growing season length estimated from NDVI via Timesat for a JER grassland site over 5 years was 221 d[16]. In average or above-average rainfall years, pasture-level SOS typically occurred in July but can start earlier (e.g. May 1, 2009).

Seasonal stages throughout the year in the study demonstrated variation similar to that of SOS dates. In the years with below-average summer rainfall (i.e., 2003–2005), the SOS and transition to the greenup seasonal stage was early, leading to long greenup stages (Fig. 4). Timing of peak NDVI most commonly occurred in late September to early October (5 of 7 years). The 32-d peak green period ranged from June 2 in 2003 to October 16 in 2006. Years with early peak green were typically low amplitude that corresponded to years with below-average precipitation. Drydown periods were either long or short, depending on the date of peak green and NDVI annual amplitude. For the 2008 AH foraging behavior study, the four trials were well-distributed throughout the growing season. The third sample period occurred during the transition from greenup to peak green. For our analysis, we classify the third period as peak green (Fig. 4).

3.2 Land-surface phenology for grass- and shrub-dominated areas

Grass and shrub areas revealed phenological profiles with distinct properties that were significantly different from each other in 3 of 7 years. Compared to the grassland areas, the NDVI profile for mesquite shrubland on the Sandy ecological site had a stronger periodicity that peaked in May 2003 through 2005. In contrast, the profile for tobosa grassland on the Clayey ecological site had greater

Table 2 Growing season metrics derived from MODIS 250-m NDVI using Timesat for 2003 to 2009

Year	Start	End	Length	Base NDVI	Date Peak NDVI	Peak NDVI	NDVI Amplitude
2003	Jan. 30	Dec. 26	329	0.135	Jun. 2	0.177	0.042
2004	Apr. 8	Dec. 23	260	0.137	Sep. 24	0.182	0.045
2005	Feb. 28	Dec. 19	294	0.144	Oct. 13	0.197	0.054
2006	Jul. 25	Dec. 9	137	0.154	Oct. 16	0.266	0.112
2007	Mar. 12	Dec. 22	284	0.155	Jul. 31	0.258	0.103
2008	Jul. 6	Dec. 13	160	0.148	Oct. 5	0.294	0.146
2009	May 1	Nov. 25	208	0.150	Oct. 8	0.196	0.046

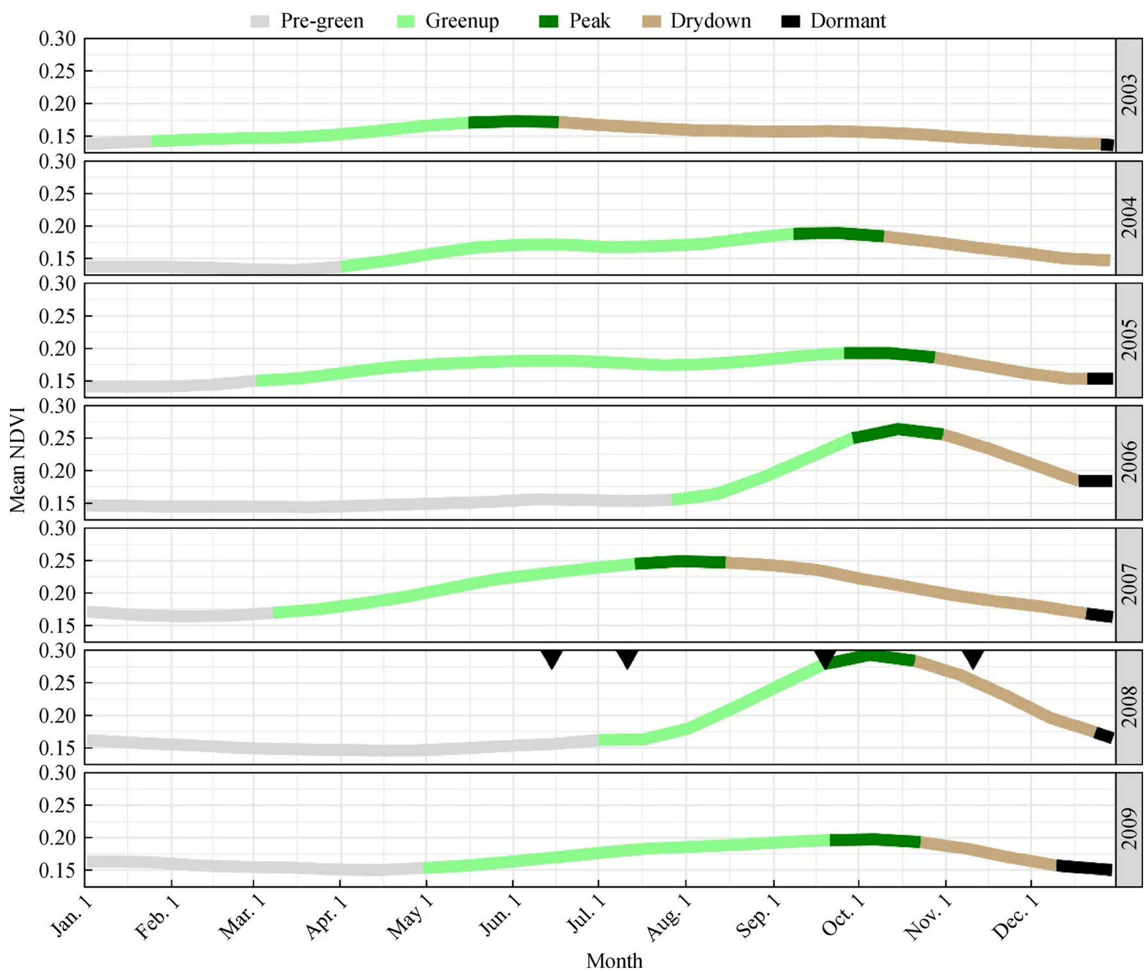

Fig. 4 Seasonal stages in pasture-level mean NDVI in 2003 to 2009. Black arrowheads in 2008 denote timing of AH grazing trials.

inter-annual variability in amplitude although timing of the peak was consistently in late September and early October. The K-S tests revealed significant differences between grass and shrub areas in 2003 ($P < 0.001$), 2006 (P = 0.010), and 2008 (P = 0.026, Fig. 5).

3.3 Cattle movement patterns in relation to NDVI and seasonal rainfall

3.3.1 Foraging activity across the landscape and seasonal stages

There was considerable spatial heterogeneity in NDVI across the seasonal stages in 2008 (Fig. 6) with greatest variance in NDVI values in the images for peak green (September 3, 2008, Fig. 6c) and drydown (November 6, 2008, Fig. 6d). The peak green seasonal stage in 2008 ranged from September 18 to October 21 with peak NDVI on October 5, 2008 (Table 2).

Compared with AH foraging locations in other seasonal stages, AH foraging locations during peak green (Fig. 6, yellow dots) were more sinuous. This is reflected in the foraging density map for September 3, (Fig. 6c). In addition, NDVI in the peak green period for locations where cows spent time foraging was significantly higher than where cows were not present (Table 3). Based on the entire data set, the percent of NDVI pixels in the pasture visited by cows was relatively stable through the first three seasonal stages, ranging from 24.3% to 25.3% (Table 3). In contrast, the percent area visited by cows in the drydown period decreased dramatically to 11.0% as foraging locations (i.e., points) were more clustered (Fig. 6d; Table 3).

3.3.2 Patterns of cattle activity in relation to seasonal variation in NDVI and precipitation

Cows traveled an average of 6.1 km·d^{-1}. Daily distance traveled by cows was unrelated to changes in pasture NDVI. However, cows tended to walk farther during weeks with higher precipitation (Table 4). A regression model including minimum NDVI, rainfall, and their interaction explained 81% of the seasonal variation in distance traveled by cows ($P < 0.01$).

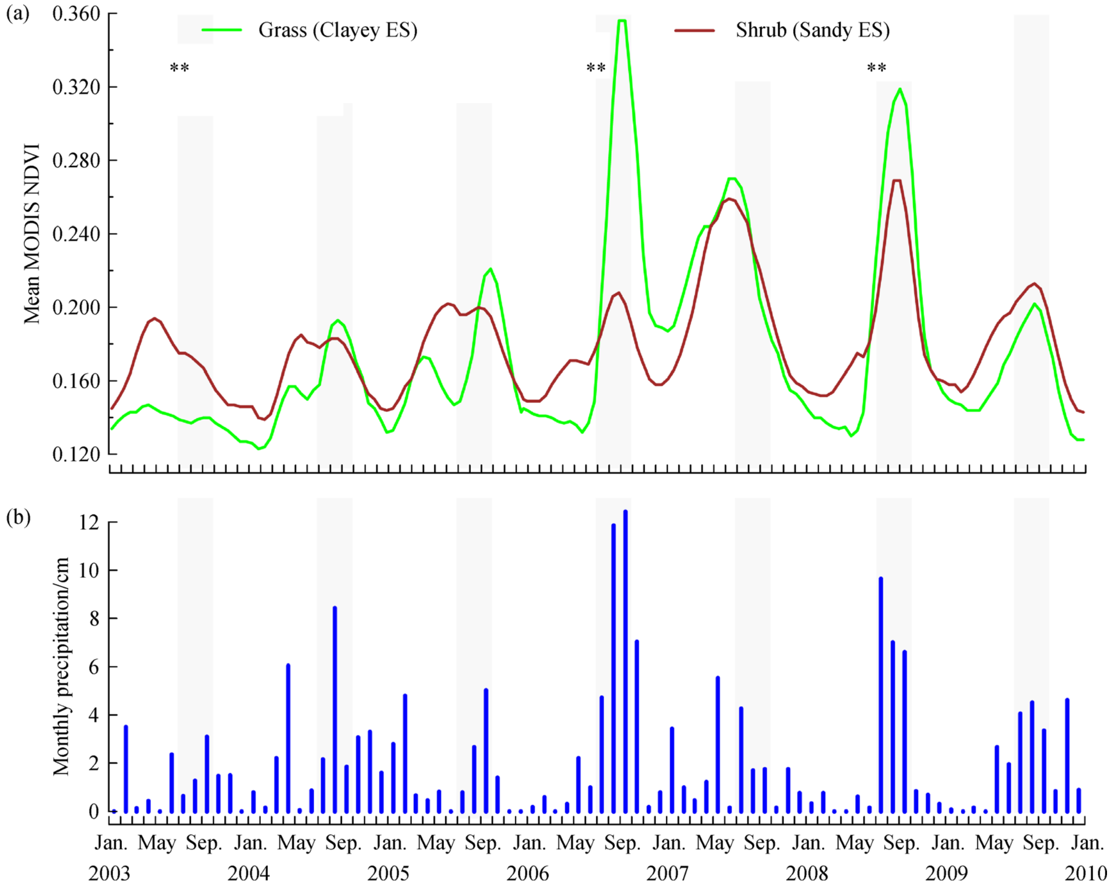

Fig. 5 (a) Seasonal profiles (i.e., fitted curves for grass and shrub) for mean NDVI derived for eight 250-m MODIS pixels for grass-dominated and shrub-dominated areas in the study pasture; (b) monthly precipitation (cm) from 2003 to 2009. K-S tests revealed significant differences between grass and shrub NDVI in 2003, 2006 and 2008 (indicated by asterisks).

Cows explored an average of 81.1 ha of the 1527-ha pasture while foraging on any given day but tended to explore smaller areas as the pasture became greener (Table 4). Conversely, daily foraging area expanded with increasing precipitation across seasonal stages (Table 1). A regression model including the same predictors as mentioned previously explained 92% of the seasonal variation in daily foraging area of cows ($P < 0.01$).

On any given day, cows allocated an average of 9.7 h to foraging activities and tended to spend more time grazing as pastures became greener regardless of weekly precipitation (Table 4). A regression model including the same predictors described above explained 85% of the seasonal variation in foraging time of cows ($P < 0.01$).

On average, cows traveled 75.3 m per grazed hectare explored but tended to travel significantly longer distances per grazed hectare (i.e., exhibited more concentrated search patterns) as the pasture became greener (Table 3). Thus, sinuosity of movement paths increased as pasture NDVI increased from pre-greenup to peak green seasonal stages. A regression model including the same predictors used for previous response variables explained 81% of seasonal variation spatial search pattern of cattle ($P < 0.01$).

4 Discussion

We demonstrated with a repeatable quantitative approach that seasons vary greatly from year to year in this arid grassland. Climatological — and more specifically — phenological context can expand the capacity for comparison and integration of findings and facilitate meta-analyses of grazing studies conducted at different locations and times of year. The methods and growing season stages from this case study in an arid environment can be applied in other rangeland types in semi-arid or more temperate climates and integrated with finer-scale studies of resource selection to enhance interpretations about livestock space use across spatial scales.

4.1 Seasonal profiles

Arid landscapes are highly variable across space and time.

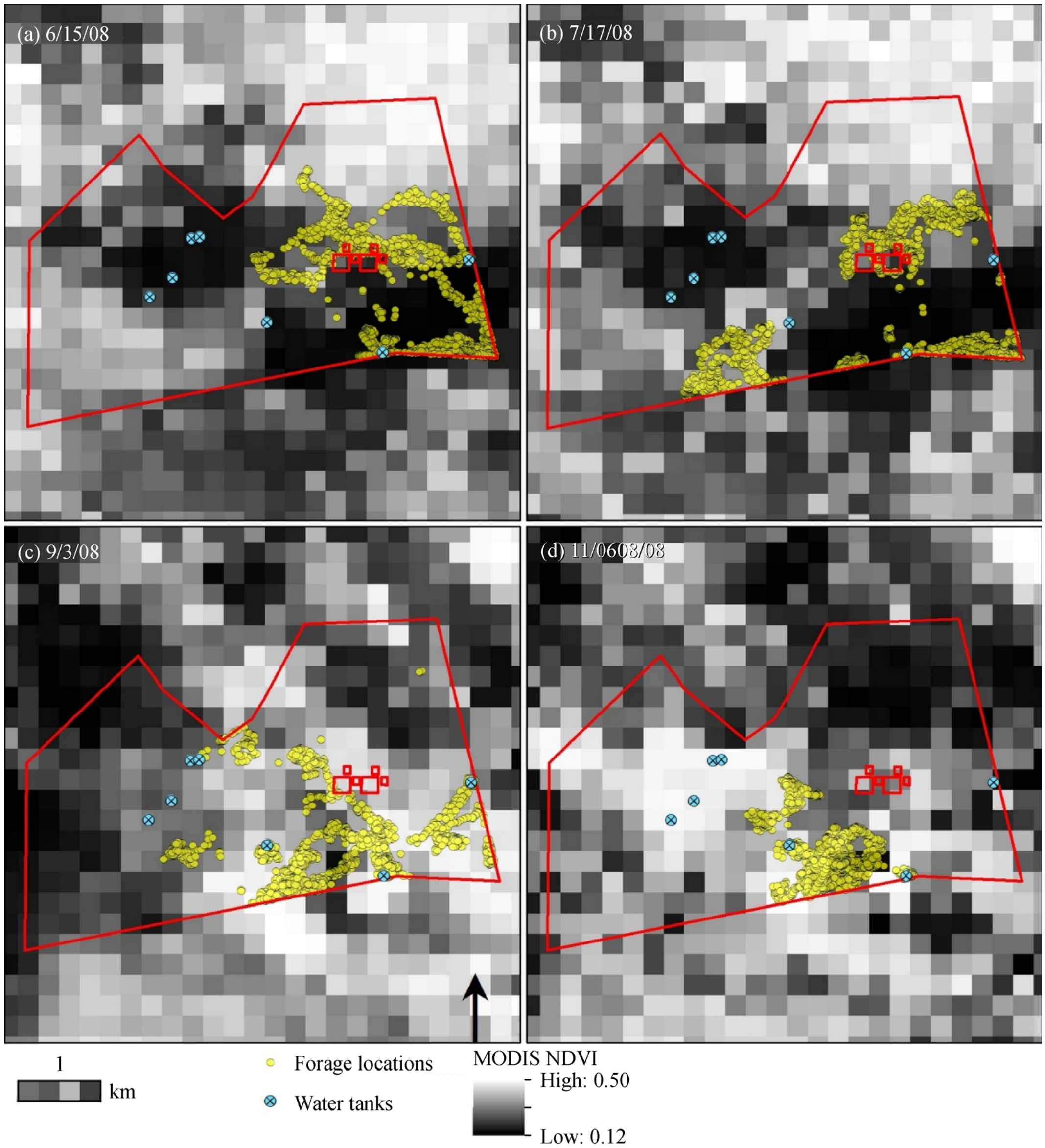

Fig. 6 Distribution of foraging locations for AH cows wearing GPS collars during four 6-d sampling periods in 2008. The NDVI image date closest to the grazing trial dates in Table 1. Small inset boxes in the pasture represent long-term study exclosures.

Significant differences in NDVI profiles for grass and shrub-dominated areas emerged and were accompanied by shifts in inter-annual NDVI distributions. The increase in NDVI amplitude of 2006 for grass-dominated sites was driven by an increase in herbaceous biomass as has been shown at other locations on the JER[39,40]. The subsequent increase in amplitude in the shrub-dominated NDVI signal in 2007 and 2008 may have been driven by widespread *Sporobolus* spp. recruitment that occurred in 2007 on the Deep Sand ecological sites dominated by mesquite[40,41].

Table 3 Comparison of NDVI values of pixels where cows foraged and where they did not forage based on GPS collar data collected over four phenological stages of the 2008 growing season

Period	No. of GPS fixes	Grazed pixels/%	NDVI grazed pixels	NDVI ungrazed pixels	t	P
Pre-greenup	4972	24.7	0.154±0.004	0.168±0.004	2.60	0.02
Greenup	4255	24.3	0.166±0.005	0.176±0.005	1.49	0.15
Peak green	2920	25.3	0.312±0.010	0.252±0.004	–5.45	< 0.01
Drydown	9064	11.0	0.244±0.008	0.229±0.005	–1.49	0.15

Table 4 Linear pairwise correlations between season-long variation in the activity of the cows and changes in pasture NDVI and rainfall

Activity of the cows[a]	NDVI[b]		Rainfall[c,d]	
	r	P	r	P
Distance traveled/(km·d^{-1})	NS	NS	0.64	< 0.01
Daily foraging area/ha	–0.38	0.04	0.42	0.02
Time spent grazing/(h·d^{-1})	0.70	< 0.01	NS	NS
Spatial search pattern/(m·ha^{-1})[e]	0.62	< 0.01	NS	NS

Note: [a] Activity of each cow (n = 5 to 10) was averaged across days (n = 6) within each of four periods (pre-greenup, greenup, peak green and drydown); [b] lowest pixel NDVI in the pasture for each of the four periods was used in the analysis (range from 0.124 to 0.207); [c] total rainfall recorded during each of the four trial periods was analyzed (range from 0 to 11.5 cm); [d] NDVI and rainfall were not correlated (r = –0.1, P = 0.95); [e] spatial search pattern and time spent grazing were positively correlated (r = 0.83, P < 0.01).

A time-series analysis (2000 to 2012) on the JER[40] revealed that increases and decreases in herbaceous biomass were responsible for the significant changes in the long term trend that was identified with MODIS NDVI.

Understanding the strengths and limitations of remotely sensed metrics is important to the integration of these tools in land management decision-making[42]. In this study, we identified significant differences in annual NDVI patterns between the grass-dominated Clayey ecological site and the shrub-dominated Sandy ecological site in years of above- and below-average rainfall. Therefore, the ability to distinguish grass- from shrub-dominated plant communities under average precipitation conditions may rely on the ratio of grass to shrub cover to reliably detect differences via MODIS NDVI.

As ecological site and state maps are increasingly integrated into land management strategies and planning processes, it is important to understand the best applications of remotely sensed metrics of land surface phenology as they relate to ecological sites. In this study, one notable contrasting pattern in NDVI was found for the Deep sand ecological site in the north-east corner of the study pasture and the Clayey ecological site (Fig. 3b; Fig. 6). The Deep Sand ecological site exhibited high NDVI early in the pre-greenup season which corresponded to patterns observed for mesquite shrubs. A similar transition to low NDVI in the drydown period occurred when the Clayey ecological site, dominated by perennial grasses, had high NDVI. This contrasting pattern highlights the importance of integrating finer-resolution ancillary data layers (e.g., field vegetation data, maps of ecological sites and/or states) to enhance interpretations of moderate spatial resolution NDVI. The relevance or explanatory power of the NDVI, as a vegetation greenness index, is not the same everywhere as it related to livestock foraging behavior.

4.2 Livestock movement patterns

Cattle GPS locations suggest that animals graze smaller areas in response to increasing NDVI but expand their foraging domain during weeks when precipitation events occur. Previous research with GPS collared livestock showed that both cattle and sheep expand and contract their daily feeding areas in response to low or high forage availability[30]. We recognize that NDVI varies temporally in terms of its nutritional value to livestock, as illustrated by Fig. 5. In addition, our results indicate that the area explored by grazing livestock might also be influenced by forage quality attributes that are not captured with MODIS NDVI. Increased NDVI in this study is possibly linked with higher nitrogen content and digestibility of the forage species[43–45], which is likely to have reduced the need for animals to search large areas of a pasture to meet their nutritional requirements. Accordingly, cows in this study showed more concentrated search patterns and spent more time grazing during weeks when pasture NDVI was high (i.e., during peak green seasonal stage).

Conversely, rainfall events apparently induced the cows in this study to increase the area they were willing to explore while grazing and to travel longer distances. A drop in summer ambient temperatures associated with rainfall events as well as increased availability of a larger number of ephemeral drinking water sources, may have relaxed thermal comfort and drinking water constraints which typically exert a strong influence on livestock feeding-site selection on rangelands[46]. Linkages between vegetation seasonal stages and beef cattle grazing behavior were also reported in a study that used GPS to describe spatial distribution of beef cows during spring greenup at a woodland site in central New Mexico. That study found that greenup dynamics (inferred by spring precipitation) significantly influenced the time cows spent grazing in each large patch (30 m × 30 m pixel), the number of times they visited the same patch over the 20-d study period, and the interval between patch re-visits[47]. Interactions among the magnitude and timing of annual greenup events and patterns of beef cattle grazing are likely to determine the ecological consequences of livestock herbivory on desert landscapes. Multi-year simulations of such plant phenology-driven effects would be critical to improve the accuracy of current predictions regarding the environmental footprint of livestock herbivory on desert rangeland.

5 Conclusions

On the ground, improved understanding of the likelihood of livestock distribution during specific seasonal stages can help inform pasture and cattle management. Use of data-driven information linking cattle movements to NDVI dynamics can help managers optimally place attractants such as salt, water and vitamin resources in the extensive pastures typical of arid ranges. Such an approach may help increase weight gains for economic outcomes and enhance distribution for environmental outcomes, thereby improving the sustainability of desert cattle production. In addition, we present an approach for contextualizing information about animal movements (in this case, livestock foraging activity) relative to patterns in landscape greenness across space and time. Integrated phenological context offers a tool to compare studies from different locations, conducted during different seasons, and in different years.

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Compliance with ethics guidelines Dawn M. Browning, Sheri Spiegal, Richard E. Estell, Andres F. Cibils, and Raul H. Peinetti declare that they have no conflicts of interest or financial conflicts to disclose.

All applicable institutional and national guidelines for the care and use of animals were followed.

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