Agriculture, Ecosystems and Environment 368 (2024) 109012

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Patch-burn management changes grazing behavior of cattle in humid subtropical grasslands

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A R T I C L E I N F O

Keywords:
Prescribed fire
Cattle behavior
Florida
Rangeland
Grazing evenness
Grazing intensity

A B S T R A C T

Humid, subtropical grazing lands utilized for cattle production are significant agroecosystems that are important for economic production, global food security, and biodiversity. Prescribed fire, an important management tool, is used for controlling woody plant encroachment, maintaining wildlife habitat, and stimulating forage regrowth. Fire also interacts with grazing to maintain grassland structure and heterogeneity. Understanding this fire-grazing interaction is important to producers because spatio-temporal cattle behavior has been linked to both livestock production and environmental impact through patterns of pasture utilization. The goal of the study was to understand how two fire regimes affected spatial and temporal grazing behavior, including grazing intensity, grazing evenness, and circadian and seasonal grazing patterns. A randomized block design experiment was established in 2017 with 16 pastures (16 ha each), at Archbold Biological Station's Buck Island Ranch in FL, USA. We examined two prescribed fire management techniques, one represented the prevailing practice of the region with prescribed fire applied to entire pastures (full burn = FB), and the other 'alternative' regime applied patch-burn (PB), in which one-third of a pasture was burned each year. Here we present results from the first year of the study, after the first patch-burns and the full burns were implemented. Global Positioning System data loggers on cows recorded 5-min location fixes to track cows and cattle grazing behavior was inferred based on distances between GPS locations. Cattle behavior was significantly different in PB vs. FB pastures. Over a year with five grazing periods, cattle spent on average 38% more time grazing in burned vs unburned patches within PB pastures. PB burned patches were also grazed with a more even spatial distribution compared to unburned patches. In contrast, in FB pastures, cattle grazing intensity and evenness were similar across the entire pasture. Time of day, temperature, season, and fire treatment all had small effects on the circadian cattle grazing patterns. Our study suggests that PB can be a management tool to manipulate cattle behavior in humid subtropical grazinglands, with potential implications for pasture utilization and beef production, carbon and nutrient cycling, and wildlife habitat.

1. Introduction

Globally, livestock grazing accounts for 25% of total land use and is the most prolific single land use (Asner et al., 2004). Tropical and subtropical grassland and savanna comprises 20.18 million km^2, or roughly 13.5%, of the world's total land area (Jenkins and Joppa, 2009) and livestock grazing is commonplace. These grazing land agroecosystems are globally important for economic productivity, food security, carbon cycling, and biodiversity (Paudel et al., 2021). The way that grazing is implemented on the landscape in terms of density and duration can have profound impacts on ecosystem services (Ren et al., 2018; Davidson et al., 2017). Finding strategies to maintain biodiversity while ensuring

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https://doi.org/10.1016/j.agee.2024.109012
Received 26 May 2023; Received in revised form 14 March 2024; Accepted 1 April 2024
Available online 6 April 2024
0167-8809/

long-term productivity are imperative as pressures from external factors, such as human population growth and climate change, strain these agroecosystems. Understanding how land management may affect cattle grazing behavior is important because it is strongly linked to energy intake and nutrition, and in turn, beef production (Gregorini et al., 2017)

Disturbances from grazing,by livestock or native herbivores, and fire are indispensable elements to maintain tropical and subtropical grasslands. Not only are these individual disturbances essential for sustaining grassland ecosystems but their interaction, termed pyric herbivory, is also important (Fuhlendorf et al., 2009). Pyric herbivory results in the spatial heterogeneity of vegetation structure whereby the vegetation in recently burned areas is kept short by grazing herbivores while in unburned areas, vegetation grows taller due to reduced grazing pressure (Fuhlendorf and Engle, 2001). This difference in vegetation structure benefits wildlife while not impacting cattle performance, and patch-burn grazing has been recommended as an important management tool to promote pyric herbivory (Allred et al., 2014; Hovick et al., 2015; Ricketts and Sandercock, 2016; Winter et al., 2014). Patch-burn grazing provides a benefit to a multitude of ecosystem services including livestock production, productivity, nutrient cycling, disease regulation, and biodiversity maintenance shown primarily in the Great Plains of North America (Scasta et al., 2016). Less is known about the impacts of patch-burn grazing in highly productive subtropical and tropical grasslands, although it has been shown to create expected patch contrasts in forage nutritive value and residual biomass, but not to the same magnitude as in temperate grasslands (Boughton et al., 2022). It is well known that cattle are attracted to vegetation regrowth in recently burned patches which generally lacks dead plant matter and contains emergent forage with greater protein content compared to mature forage, however the spatial and temporal magnitude of this behavior are not well understood, especially in subtropical humid grazing lands (Allred et al., 2011; Boughton et al., 2022).

Grazing intensity and distribution have long concerned the cattle production community in attempts to improve range productivity and condition (Stoddart and Smith, 1955). Understanding the mechanisms that influence grazing intensity and distribution is vital to promote sustainable production and ecosystems of cultivated and natural grazing lands. Environmental drivers of grazing behavior may include topography, water resources, and forage availability, and human management decisions such as implementation of fire, placement of supplemental feed, installation of water troughs, and fences all affect grazing intensity and distribution (Bailey et al., 1996). With the advancements in Global Positioning System (GPS) receivers and battery technology, cattle can be tracked at fine spatial and temporal scales and behavior inferred based on their movement patterns (Augustine et al., 2023; Augustine and Derner, 2013; Clark et al., 2006). Periods of cattle grazing can be distinguished from other behaviors (i.e. resting, traveling) and can be identified by examining the velocity of sequential GPS locations through time. With known grazing locations, spatial and temporal grazing patterns can be identified, and the impacts of management regimes and environmental drivers can be assessed (Raynor et al., 2021).

In this study, we examined two pasture management techniques to evaluate the spatial and temporal distribution of cattle grazing in southern Florida grazing lands. The first technique, often referred to as patch-burn (PB) grazing, is a method in which portions of the pasture are burned in rotation one year after another to create a heterogeneous cattle grazing and vegetation structural distribution at the pasture scale across years (Fuhlendorf and Engle, 2001). We set up a three-year burn rotation with one portion burned each year. In the second technique a prescribed full-burn (FB) of the entire pasture was conducted at the beginning of the first study year to create a more homogeneous cattle and vegetation distribution at the pasture scale, which would not be burned again until year four. The second management technique follows prevailing practices (Boughton et al., 2022). The specific objectives were to examine the effect of fire management regimes on 1) the spatial distribution of grazing intensity by cattle; 2) the evenness of cattle grazing; and 3) the temporal distribution of cattle grazing.

Since fire removes dead vegetation and promotes the regrowth of forage with greater protein content (Allred et al., 2011), within PB, under our first objective, we expected cattle to graze recently burned areas more intensively than unburned areas shortly after the application of fire. Further, because cattle maintain this short growing forage after fire, positive feedback of regrazing the burned area was expected to maintain the greater intensity of grazing in the recently burned areas compared to unburned areas over an even longer time period. Within FB, cattle would only have the choice of recently burned vegetation, therefore, grazing intensity was expected to be initially more homogeneous across the whole pasture because it lacked the choice between a smaller burned portion and larger unburned portions of PB pastures. Therefore the grazing intensity distribution would not be driven by fire but with increasing time-since-fire following environmental gradients, for example elevation (e.g.(Raynor et al., 2021)).

Our second objective was to evaluate the evenness of cattle grazing distribution in relation to PB treatments compared to FB pastures. Cattle are naturally selective grazers and select particular areas based on many factors acting at different scales (e.g. forage palatability and quality, topography, distance to water (Bailey et al., 1996)). This selectivity leads cattle to graze some areas and avoid others, resulting in a clustered spatial pattern and lower utilization of the pasture focusing on the most palatable vegetation with consequences for cattle weight gains (Augustine et al., 2023). Since the use of fire removes dead vegetation and can reduce plant species that may be abundant or unpalatable, and even make some species more palatable, within PB on burned areas, we expected cattle to graze with less spatial clustering compared to unburned areas. In contrast, in FB pastures, we expected no difference in spatial clustering across the pasture driven by a burn patch (i.e. all of pasture is burned), although other drivers may impact spatial clustering.

Lastly, we examined the temporal distribution of cattle grazing and the impact of fire regime. For PB to be an appropriate tool to be used in livestock enterprises it should not impact the daily grazing behavior of cattle. One potential concern with utilizing PB was that this practice has less area of post-fire high protein forage compared to FB, especially in year one of the fire rotation. Therefore, cattle in PB pastures may have to utilize poorer quality unburned forage leading to changes in circadian grazing patterns. To address this concern, we compared daily grazing patterns of the two fire treatments within the whole pasture across seasons. It's widely accepted that cattle graze less during extreme warm periods (Ehrenreich and Bjugstad, 1966). Unlike higher latitudes with continental weather patterns that can experience wide ranges in temperature, humid, subtropical grasslands are generally characterized by mild, dry winters and warm/hot, wet summers. However, there is little data characterizing the year-long temporal grazing distribution of cattle in humid, subtropical grazing lands or with fire.

2. Methods

2.1. Study area

Cattle behavior monitoring took place on Archbold Biological Station's Buck Island Ranch (BIR; 27∘09'N, 81∘11'W). BIR is a 4170 ha commercial cow-calf operation located southeast of Lake Place, Florida in the headwaters of the Everglades watershed (Swain et al., 2013). The ranch maintains a cattle herd of ~3000 cow/calf pairs. The cattle are a mixed herd consisting of Brahman, Angus, and Charolais breeds. Roughly half the pasture area at BIR consists of improved pasture (IMP) forages dominated by bahiagrass (*Paspalum notatum* Flugge). Selected IMPs are fertilized roughly every two years with N and periodically limed. The other half of BIR consists of semi-native pasture (SNP) with forage species that include a diverse mixture of bahiagrass, broomsedge bluestem (*Andropogon virginicus* L.), purple bluestem (*Andropogon cretaceus* (Elliott) C. Mohr), panic grass (*Coleataenia longifolia* Torr.), and common carpetgrass (*Axonopus fissifolius* (Raddi) Kuhlm.). Management in SNPs is minimal and both pasture-types have had recurring application of prescribed fire to improve forage quality and control woody vegetation. Thirty-year mean precipitation at BIR is 1324.6 mm with, on average, 353.1 mm occurring between January and June and 627.6 mm occurring between June and August (NOAA – NCDC 2019). Thirty-year mean maximum and minimum temperature at BIR is 29.0°C and 15.0°C respectively (NOAA – NCDC 2019). 2017 weather data was collected locally at BIR from a weather station logging at 15-minute intervals (BIR_LTAR, CR1000 Campbell Scientific data logger with TE525WS-L2 Texas Electronics rain gauge and Rotronic HygroClip2 temperature and humidity probe). In 2017, BIR received 1361.2 mm annual precipitation, 153.2 mm between January and June, and 563.6 mm during August and September due in part to Hurricane Irma. Soils at BIR are dominated by sand with slopes between 0 and 2 percent (Soil Survey Staff 2019).

2.2. Study design

We established 16 study pastures within BIR in 2016 (Boughton et al., 2022; Fig. 1) as part of a large pasture-scale study to compare the effect of two fire regimes on multiple regulating and supporting

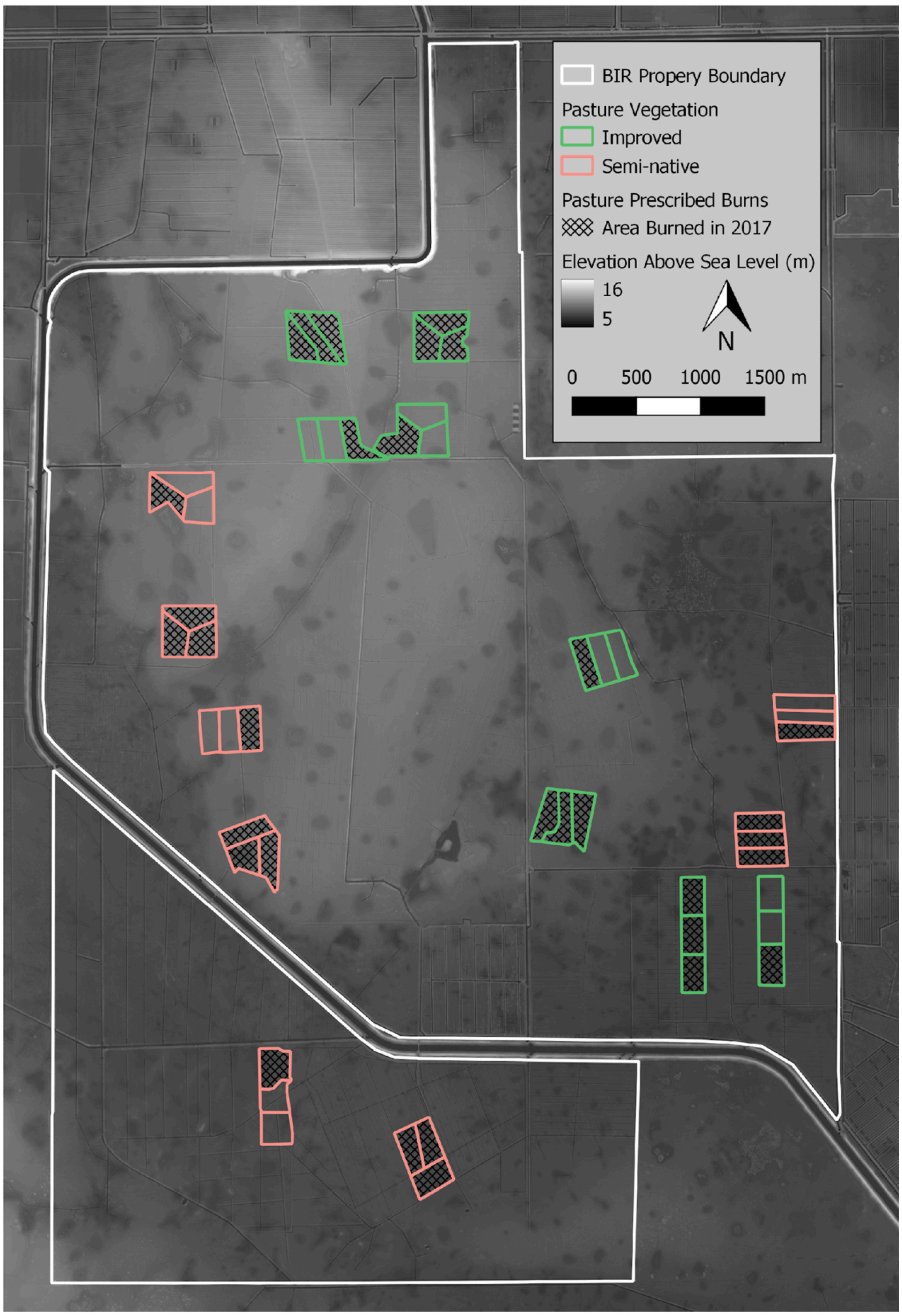

Fig. 1. Study site location at Archbold Biological Station's Buck Island Ranch (BIR). Experimental pastures are outlined in green (Improved pastures) and red (Semi-native pastures). Interior pasture lines denote divisions between patches in patch-burned pastures or sectors in fully burned pastures. Hatched areas represent areas treated with prescribed fire. Lighter areas are higher elevation than darker areas.

ecosystem services, including greenhouse gas regulation, water use efficiency, forage production/quality, and plant diversity (Boughton et al., 2022). This study is part of the Archbold-University of Florida US Department of Agriculture Long-term Agroecosystem Research (LTAR) site's "Common Experiment" in which the overall objective is to compare production, environmental, and social outcomes of an aspirational treatment and a business-as-usual treatment (Kleinman et al., 2018; Spiegal et al., 2018). In this experiment, PB is the aspirational treatment and FB is the prevailing practice treatment.

Pastures were established based on criteria including forage type, avoidance of wetlands, elevation, soil types, and existing fence lines. Pastures ranged in size from 15.6 to 18.3 ha with a mean of 16.5 ha. A randomized block design (paired pastures based on location) was established and pastures were divided evenly into two treatments: FB, a full pasture prescribed burn the initial year of the study and PB, a patch prescribed burn where a different one-third pasture patch was burned each year of the study. FB and PB pastures were all divided into three equal area "sectors" for stratified random sampling and for comparisons of equal areas in FB pastures to patches in PB pastures. Pastures were also divided evenly between IMP (n=8) and SNP (n=8) but pasture type was not assessed in this analyses, due to unforeseen drought, see below. Prescribed fires were conducted between 30 January 2017 and 8 February 2017. IMPs were stocked with 32 cows and SNPs were stocked with 15 cows. Cattle were introduced into PB pastures beginning in early February. Cattle herds (n=8) were rotated between each paired PB and FB pastures every 4–8 weeks and total annual animal use days of each pasture within a pasture-type was kept as similar as possible (Mean AUM ha^{-1} IMP = 56.32; SNP = 5.10; Appendix 1). We refer to the time span where cattle are in a particular treatment as grazing periods. Cattle were stocked in IMPs year-round while SNPs contained cattle between February and late July. Cattle had unrestricted access to a single water trough in each pasture and were provided protein supplement. This study presents results of cattle behavior from one year (2017) following the implementation of the first patch-burns and full-burn treatments.

To estimate cattle activity, we utilized GPS collars deployed for a period of at least six months after which new collars were attached. Collars consisted of GPS unit and battery, enclosed PVC tube housing, nylon collar, and a counterweight to orient the PVC tube containing the GPS unit on top of the cow's neck. The GPS unit was set to record a location every 5 minutes (Perthold Engineering LLC). GPS units were powered by a 3.6 V, 14.5 Ah, lithium thionyl chloride battery which, in combination with logging interval, allowed active deployment of up to 12 months. Collars were attached to 32 cows and were randomly separated evenly into the 8 treatment herds. This resulted in initial deployment of four collars per herd for each paired set of pastures creating grazing records for the 16 experimental pastures. Following ranch cattle working schedules, 4 herds had initial GPS units removed and new GPS deployed. During deployment, 6 GPS units showed signs of water damage and though data was recoverable, had shortened recording time spans. All collars were tested for accuracy of location against Position Dilution of Precision (PDOP) and no relationship was found to allow use of PDOP as a screening tool to remove low accuracy positions. Cattle collaring followed University of Florida IACUC protocol 201808495.

2.3. Data analysis

Once downloaded from the GPS units, data were managed and manipulated using PostgreSQL and PostGIS. We removed all GPS locations of obvious error occurring outside treatment pasture boundary fences. We also removed GPS locations coinciding with the day cattle were introduced and removed from pastures. Three cattle activity categories were classified, resting, grazing, and traveling, established based on distance between successive GPS locations (Peinetti et al., 2011; Signer et al., 2019; Ungar et al., 2005). Resting activity was classified as distance less than 10 m between successive GPS locations. Grazing activity was classified as distance from 10 to 100 m between successive GPS locations. These movement derived grazing points likely capture both search and consumption of forage and it was not possible to separate these in the current study. Traveling activity was classified as distance greater than 100 m between successive GPS locations (Peinetti et al., 2011). GPS locations that occurred around watering troughs and protein supplementation were retained in the data set but were typically classified as resting activity. The distribution of grazing behavior categories of grazing, resting and traveling were consistent with other studies supporting the validity of these results (Ungar et al., 2005).

Data from four SNP, two PB and two FB, were removed from analysis due to drought which caused inconsistent rotations of cattle herds between pastures and inability to maintain the herd in confined pastures. Therefore, in our analyses, to make our sample size as robust as possible we pooled data from IMP and SNP pastures and we were unable to test the impact of pasture-type in our analyses due to low sample size. As our data is averaged to the unit of replication (pasture), only pastures and time periods with greater than 2 active GPS collars were used in analyses. Where appropriate Levene's test for homogeneity of variances across treatments was utilized and no significant differences were found.

To examine cattle grazing intensity between burned and unburned areas of PB pastures, we conducted a first-order pattern analysis of points categorized as grazing (Baddeley et al., 2015). First, we calculated the daily proportion of use for each patch or sector (a third of each pasture) within a pasture by dividing the number of grazing locations in a patch by the pasture total for each day in 2017. We then conducted a logistic regression with a binomial family distribution for FB or PB using proportion of use as a response variable and modeled by fixed effects of treatment patch (i.e. PB-Burn, PB-Unburn, or FB) with time interaction (i.e. week) and a random variable of pasture. Since cattle were rotated between treatment pastures resulting in gaps within our time series, we modeled each grazing period separately. There were five grazing periods (rotations) in each treatment in 2017, with period length determined by a target stubble height of 7 cm (Appendix 1). The R package lme4, with the glmer function was used.

To analyze the distribution of cattle grazing we calculated evenness, a second-order point process, using a 30 ×30 m grid of cells across the study area. For each cell the number of grazing points was calculated for each week of the study year combining data from all collared cows. Due to patch and pasture boundary shape and orientation, some cells were less than 900 m^2. To account for cell size difference, we multiplied the cell size proportion and point counts per cell to give a scaled (to 900 m^2) value of grazing point counts per area. Cells smaller than 50 m^2 were removed from analyses due to excessive influence on weighting factor. Since we had more grazing locations within the burned patch based on the grazing intensity analysis, we weighted each cell's count by the total grazing points for that pasture. This enabled us to compare differences in grazing evenness among patches and sectors by calculating the index of dispersion (Perry et al., 2002) for each patch/sector using the formula:

$$ID = \frac{\sigma^2}{\mu}$$

where σ^2= variance, μ= mean. To compare the index of dispersion among patches of PB and FB pastures, we used a general linear model to assess the main effect of patch (PB-Burned, PB-Unburned1, PB-Unburned2, FB-Sector1, FB-Sector2, FB-Sector3) during each grazing period. Grazing periods were combined for each treatment resulting in five separate analyses, e.g. grazing period 1 of PB and FB were analyzed together. Post-hoc pairwise comparisons were made to assess patch differences using the emmeans library in R. Index of dispersion was log transformed to achieve normality prior to analyses. We had limited power to assess interaction of patch and week within a grazing period, but we graphed data by week to enable visual comparisons of cattle dispersion to proportion of grazing (Fig. 3A,B). Lower index of dispersion values represents greater evenness of grazing within an area.

Additionally, for each grazing period, we analyzed the main effect of treatment (FB vs. PB) on index of dispersion.

Circadian grazing patterns were analyzed across 2017 using a linear harmonic regression. Harmonic regression incorporates a transformation of the circular variable of hour into Fourier terms to model periodicity that naturally occurs in the data. To examine grazing occurrence, we obtained the mean number of grazing points per collared cow per pasture for each hour in 2017. This was expressed as multiplying the number of grazing points per hour x 5 (i.e. 12 pts = 60 minutes grazing). Our *a priori* model covariates included first and second Fourier terms, season, temperature, and burn treatment (FB and PB). We reduced season to three periods based on climatic patterns and coinciding with forage development phases. Cool-dry season, from 1 January to 15 May, coincides with forage emergence from dormancy and early development. Hot-wet season, from 16 May to 15 September, coincides with monsoonal rains and peak biomass production. Warm-wet season, from 16 September to 31 December, coincides with seed development and ends with senescence due to freeze conditions in a typical year. We used multi-model inference to narrow down our covariates into a set of best models (Burnham and Anderson, 2001). Starting with our global model, we developed subsequent candidate models by removing the covariates season, temperature, and treatment. We then ranked models using Akaike's Information Criterion for small sample sizes (AICc) to select the models having the greatest support. As a higher level analysis, we conducted an analysis of variance of grazing time (mean daily grazing time (hours/cow)) by season and fire treatments. The R package bblme with function aicctab was used.

All data analyses were conducted in program R Studio 2023.03, R version 4.2.2 (R Core Team, 2021).

3. Results

3.1. Cattle grazing intensity

Grazing accounted for 58.3% of all cattle activity. Resting and traveling activity accounted for 38.1% and 3.5%, respectively. In 2017, 1,061,497 points were classified as grazing from the 1,819,885 total points. Examining grazing intensity of patches within PB pastures, we observed a significant influence of patch, time, and the interaction of patch and time for all five grazing periods on grazing proportion ($p<0.001$; Table 1a; Fig. 2a.). In PB pastures, coefficients were consistently positive in burned patches compared to unburned patches, indicating that cattle spent more time in burned patches. Over five grazing periods in one year, cattle spent 38% more time grazing in the burned patch. In FB pastures we similarly observed a significant influence of sector, time, and interaction of sector and time ($p < 0.01$; Table 1b; Fig. 2b). However, the sign of the coefficients was inconsistent between the interaction of time and sectors across the grazing periods.

3.2. Cattle grazing evenness

The PB burned patch had a significantly smaller index of dispersion (e.g. greater evenness) compared to unburned patches and compared to all three FB sectors in grazing periods 1, 2, and 3 (Table 2; Fig. 3a). The PB unburned patches did not differ in index of dispersion in any grazing period (Table 2). In FB pastures, the index of dispersion among sectors did not differ from each other in any grazing period (Table 2; Fig. 3b). In grazing periods 4 and 5, there were very few significant differences among PB and FB patches with only idiosyncratic differences between FB sectors and PB unburned patches (Table 2). Over the whole year, PB, with the combination of the burned patch and two unburned patches, had more even grazing than FB at the pasture scale (coeff: −0.14, SE = 0.05, p=0.005).

3.3. Cattle grazing and time of day

The Fourier model including the interaction of season, temperature, and fire treatments had the lowest AICc and highest weight compared to other candidate models (Table 3). This model by far had the greatest support with ΔAICc of 103 from the next plausible model. The model receiving the least support contained only the fourier terms. Adding the interaction of season, temperature, and fire treatment increased the explanatory power from $R^2_{adj} = 0.16$ to $R^2_{adj} = 0.26$ (Table 3; Fig. 4a). Daily grazing time (hours) was significantly impacted by an interaction of season and treatment (Season x treatment, $F_{(2319)}=3.72$, p=0.03) (Fig. 4b). In the cool-dry (Jan-May) season, grazing time did not differ significantly between FB and PB, but in hot-wet (May-Sept) and warm-wet (Sept-Dec) seasons, grazing time in PB was significantly greater than FB (Fig. 4b; FB-hot-wet vs. PB hot-wet, −0.26 ± 0.09, p=0.04; FB-warm-wet vs. PB-warm-wet, −0.37 0.09, p=0.001). The difference was on average 16 minutes more grazing time in the hot-wet season and 22 minutes more in the warm-wet season in PB vs. FB.

4. Discussion

The humid subtropics host some of the most productive grazing lands in the world. Our results show that in humid subtropical patch-burned pastures, cattle will graze more intensely on recently burned patches compared to unburned patches throughout the year (Fig. 2a, b), demonstrating a strong fire-grazing interaction. Further, on recently burned patches in patch-burned pastures, cattle showed a trend of grazing in a more even spatial distribution compared to unburned patches and full-burned pastures (Fig. 3a, b). Even though fire treatment has strong spatial effects on grazing behavior, overall the circadian pattern and total amount of daily time spent grazing between treatments was similar (Fig. 4a,b), suggesting that fire can be used to direct cattle grazing in a targeted approach to manage grasslands without harming

Table 1
General linear mixed model results of covariate influence on proportion of grazing in each of five grazing periods (GP) within a) patch burn (PB) and b) full burn (FB) treated pastures. Values in bold are significant at p <0.05. See Appendix 1 for definition of Grazing Periods.

	GP 1		*GP 2*		*GP 3*		*GP 4*		*GP 5*	
Patch-Burn	*Coef.*	*Std Err*	*Coef.*	*Std Err*	*Coef.*	*Std Err*	*Coef.*	*Std Err*	*Coef.*	*Std Err*
Burned Patch	**180.30**	**7.89×10^{-3}**	**198.30**	**9.05×10^{-3}**	**80.96**	**1.50×10**	**805.10**	**1.56×10^{-2}**	**503.8**	**1.75×10^{-2}**
Unburned Patch 1 (UB 1)	**-20.30**	**1.41×10^{-2}**	**-108.90**	**1.52×10^{-2}**	**52.88**	**1.57×10**	**-567.0**	**2.24×10^{-2}**	**-189.5**	**3.14×10^{-2}**
Unburned Patch 2 (UB 2)	**-185.10**	**1.40×10^{-2}**	**-98.13**	**1.42×10^{-2}**	**-28.36**	**1.96×10**	**-220.4**	**3.31×10^{-2}**	**-375.80**	**3.04×10^{-2}**
Time	**-0.01**	**4.18×10^{-7}**	**-0.01**	**4.64×10^{-7}**	**0.00**	**8.63×10^{-4}**	**-0.004**	**8.03×10^{-7}**	**-0.03**	**9.10×10^{-7}**
Time x UB 1	**0.01**	**7.80×10^{-7}**	**0.02**	**8.41×10^{-7}**	0.00	1.25×10^{-3}	**0.08**	**1.25×10^{-6}**	**0.04**	**1.71×10^{-6}**
Time x UB 2	**0.02**	**7.73×10^{-7}**	**0.02**	**7.89×10^{-7}**	**0.02**	**1.42×10^{-3}**	**0.06**	**1.79×10^{-6}**	**0.05**	**1.66×10^{-6}**
Full-Burn										
Sector 1	**8.91**	**1.12×10^{-2}**	**-55.63**	**7.24×10^{-3}**	**175.80**	**6.74×10**	**175.50**	**1.30×10^{-2}**	**-231.20**	**1.55×10^{-2}**
Sector 2	**-20.18**	**2.04×10^{-2}**	**75.11**	**1.55×10^{-2}**	**578.00**	**7.42×10**	**-253.10**	**2.27×10^{-2}**	**-11.03**	**2.28×10^{-2}**
Sector 3	**8.83**	**2.01×10^{-2}**	**-7.28**	**1.14×10^{-2}**	**-718.40**	**6.71×10**	**111.10**	**1.97×10^{-2}**	**362.80**	**2.61×10^{-2}**
Time	**0.00**	**6.22×10^{-7}**	**0.00**	**3.82×10^{-7}**	**-0.01**	**3.87×10^{-3}**	**-0.01**	**6.58×10^{-7}**	**0.01**	**7.76×10^{-7}**
Sector 2 x Time	**0.00**	**1.13×10^{-6}**	**0.00**	**8.45×10^{-7}**	**-0.02**	**5.76×10^{-3}**	**-0.02**	**1.24×10^{-6}**	**-0.01**	**1.26×10^{-6}**
Sector 3 x Time	**0.00**	**1.11×10^{-6}**	**0.00**	**6.30×10^{-7}**	**0.05**	**5.46×10^{-3}**	**-0.04**	**1.09×10^{-6}**	**-0.03**	**1.42×10^{-6}**

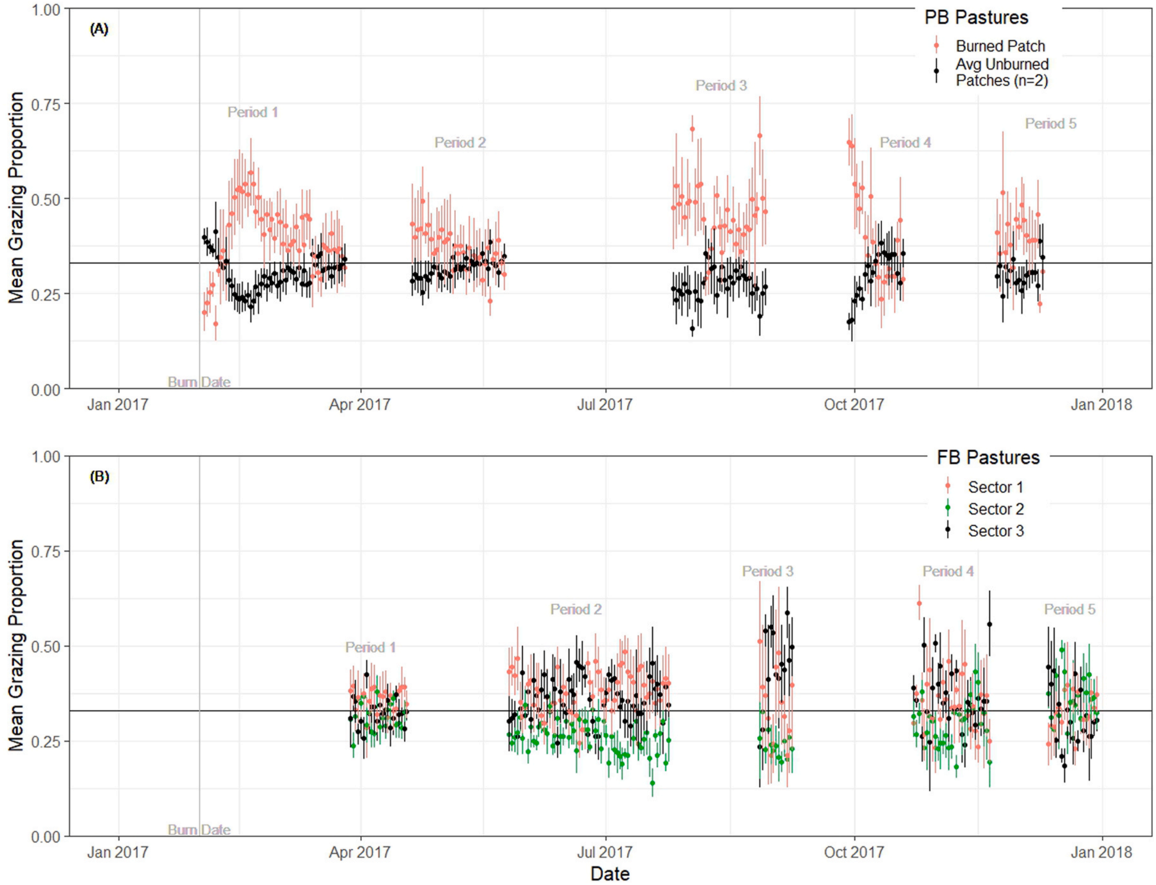

Fig. 2. (A). Mean ± SE proportion of grazing per week in patch burn treated pastures. (B). Mean ± SE proportion of grazing per week in full burn treated pastures. Grey vertical line indicates date when prescribed burns were conducted. Black horizontal line indicates grazing of a patch at 33%, the value if all three patches are grazed equally. Cattle herds were rotationally managed between patch-burned (PB) and full burned (FB) treatments.

Table 2
Pairwise contrasts of mean index of dispersion between patches and sectors in each of five grazing periods (GP) within patch burn (PB) and full burn (FB) treated pastures. FB S1 = FB Sector 1; FB S2 = FB Sector 2; FB S3 = FB Sector 3; PB UB 1 and PB UB 2 = unburned patches within PB treatment pastures. * indicates marginal significance, bold indicates significant p-values of 0.05 or less.

	GP 1			*GP 2*			*GP 3*			*GP 4*			*GP 5*		
Contrast	*Coef.*	*SE*	*p value*	*Coef.*	*SE*	*p value*	*Coef.*	*SE*	*p value*	*Coef.*	*SE*	*p value*	*Coef.*	*SE*	*p value*
FB S1 - FB S2	-0.06	0.19	1.00	0.05	0.13	1.00	-0.56	0.28	0.36	-0.18	0.14	0.79	-0.03	0.16	1.00
FB S1 - FB S3	-0.10	0.19	1.00	-0.13	0.13	0.94	-0.75	0.28	0.09*	0.08	0.14	0.99	0.05	0.16	1.00
FB S1 - PB Burned	0.46	0.17	0.09*	**0.77**	**0.15**	**<.0001**	0.09	0.24	1.00	-0.07	0.15	1.00	0.44	0.18	0.15
FB S1 - PB UB1	-0.41	0.17	0.17	0.12	0.15	0.96	**-0.70**	**0.24**	**0.04**	-0.30	0.15	0.37	0.21	0.18	0.84
FB S1 - PB UB2	-0.31	0.17	0.47	0.27	0.15	0.46	-0.49	0.24	0.31	-0.33	0.15	0.26	**0.52**	**0.18**	**0.05**
FB S2 - FB S3	-0.04	0.19	1.00	-0.18	0.13	0.76	-0.19	0.28	0.98	0.27	0.14	0.43	0.08	0.16	1.00
FB S2 - PB Burned	**0.51**	**0.17**	**0.04**	**0.72**	**0.15**	**<.0001**	0.64	0.24	0.08*	0.12	0.15	0.97	0.47	0.18	0.10
FB S2 - PB UB1	-0.35	0.17	0.31	0.07	0.15	1.00	-0.14	0.24	0.99	-0.12	0.15	0.97	0.24	0.18	0.75
FB S2 - PB UB2	-0.25	0.17	0.68	0.22	0.15	0.69	0.07	0.24	1.00	-0.14	0.15	0.93	**0.55**	**0.18**	**0.04**
FB S3 - PB Burned	**0.55**	**0.17**	**0.02**	**0.89**	**0.15**	**<.0001**	**0.84**	**0.24**	**0.01**	-0.15	0.15	0.92	0.39	0.18	0.24
FB S3 - PB UB1	-0.31	0.17	0.46	0.25	0.15	0.56	0.05	0.24	1.00	-0.38	0.15	0.13	0.16	0.18	0.94
FB S3 - PB UB2	-0.21	0.17	0.82	0.40	0.15	0.09*	0.26	0.24	0.88	-0.41	0.15	0.08*	0.47	0.18	0.10
PB Burned - PB UB1	**-0.87**	**0.15**	**<.0001**	**-0.65**	**0.16**	**0.00**	**-0.78**	**0.18**	**0.00**	-0.23	0.16	0.69	-0.23	0.19	0.84
PB Burned - PB UB2	**-0.76**	**0.15**	**<.0001**	**-0.50**	**0.16**	**0.03**	**-0.58**	**0.18**	**0.02**	-0.26	0.16	0.57	0.08	0.19	1.00
PB UB1 - PB UB2	0.10	0.15	0.98	0.15	0.16	0.94	0.21	0.18	0.85	-0.03	0.16	1.00	0.31	0.19	0.61

cattle production as found in other studies (Allred et al., 2014, Limb et al., 2011). In fact, it has been shown that forage quality is enhanced in PB pasture vs. FB pastures and may benefit cattle production (Boughton et al., 2022).

Disproportionate increased grazing of cattle in recently burned areas is well documented in other rangeland systems (Allred et al., 2011; Archibald et al., 2005; Fuhlendorf et al., 2009; Sensenig et al., 2010; Vermeire et al., 2004; Vinton et al., 1993). However, ours is the first to demonstrate this effect in humid, subtropical grazing lands and in particular, the long duration of this effect, at least 10 months post-fire. The attractiveness of the recently burned patch is likely due to similar reasons seen in other studies examining pyric herbivory whereby post-fire forage regrowth contains higher protein content (e.g.(Eby et al., 2014)) and reduced litter and dead vegetation in the burned area. In our pastures we also observed an increase in crude protein and digestibility of forage in recently burned compared to unburned areas

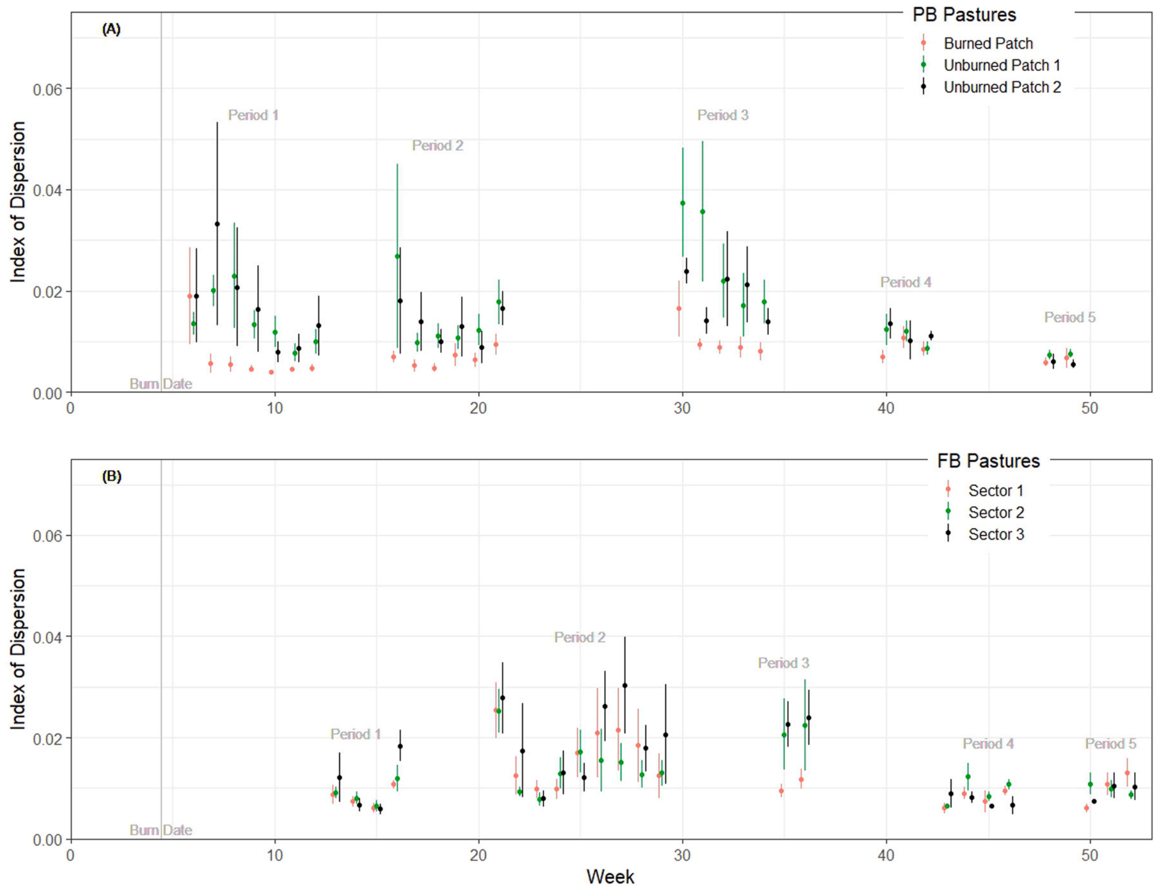

Fig. 3. (A). Mean ± SE index of cattle dispersion per week in patch burn treated pastures. (B). Mean ± SE index of dispersion per week in full burn treated pastures. Grey vertical line indicates date when prescribed burns were conducted. Cattle herds were rotationally managed between patch-burned (PB) and full burned (FB)treatments.

Table 3
Ranked candidate models of circadian grazing patterns using Akaike's Information Criterion for small sample sizes (AICc) with K number of parameters.

	Parameters	K	AICc	ΔAIC	Weight	Log likelihood	Adj - r^2
1	Fourier terms * Season * Temp * Treatment	7	19665	0	1	-9685	0.26
2	Fourier terms * Season * Treatment	6	19768	103	0	-9810	0.24
3	Fourier terms * Season * Temp	6	19792	127	0	-9822	0.24
4	Fourier terms * Season	5	19930	265	0	-9928	0.22
5	Fourier terms * Temp * Treatment	6	20003	338	0	-9953	0.22
6	Fourier terms * Temp	5	20175	510	0	-10063	0.20
7	Fourier terms * Treatment	5	20337	670	0	-10143	0.18
8	Fourier terms	4	20490	825	0	-10232	0.16

(Boughton et al., 2022). Further, urine and dung deposition in recently burned and intensely grazed areas may maintain forage nutritive value in a positive feedback loop for longer time periods. However, our study showed that cattle spent an average of 38% of their grazing time on recently burned areas that comprised 1/3 of the landscape. This is on par with cattle selection for burned areas in semi-arid rangelands (Augustine and Derner, 2014) but not as strong as in temperate, mesic grassland, where grazers spent 58–68% of their time on average on burned areas that comprised 25% of the landscape (Allred et al., 2011). The weaker fire-grazing interaction strength may be driven by lower productivity in semi-arid rangelands, lower forage nutritive value in subtropical C4 dominated grasslands, or suboptimal stocking rates (Augustine and Derner, 2014; Scasta et al., 2016; Boughton et al., 2022).

Even pasture utilization and dung distribution is often a management goal in pasture systems (Vendramini et al., 2014), and our study shows that patch-burning may be one potential strategy to achieve this. Cattle grazed more evenly the first half of the year in recently burned patches compared to unburned patches of PB and FB pastures (Fig. 3a,b). This pattern of more even utilization under higher grazing intensities agrees with other studies (Venter et al., 2019). In FB pastures we did not observe significant differences between sectors during any grazing period (Table 2, Fig. 3b). This lack of difference is due to the benefits to post-fire forage being similar across all three sectors. As time since fire increases, in FB systems, it is expected that decreased grazing evenness (i.e. clustering) will likely occur. Interestingly, in the warm-wet season (Sept – Dec) of both FB and PB, cattle grazing became more even, possibly driven by the end of the growing season and reduced forage production (Fig. 3a,b). This is one of the first studies to show that patch-burning can be used to manipulate both intensity of grazing and even distribution of grazing. The impact of PB on intensity was a longer-lived effect than the effect on evenness of use. As time since fire increases in burned patches, the intensity of use remained high but the clustering of grazing increased 35 weeks post-fire. Increased evenness of grazing distribution may not always be a beneficial management goal, as more even grazing occurring in larger herd rotational systems has been associated with lower cattle weight gains (Augustine et al., 2023).

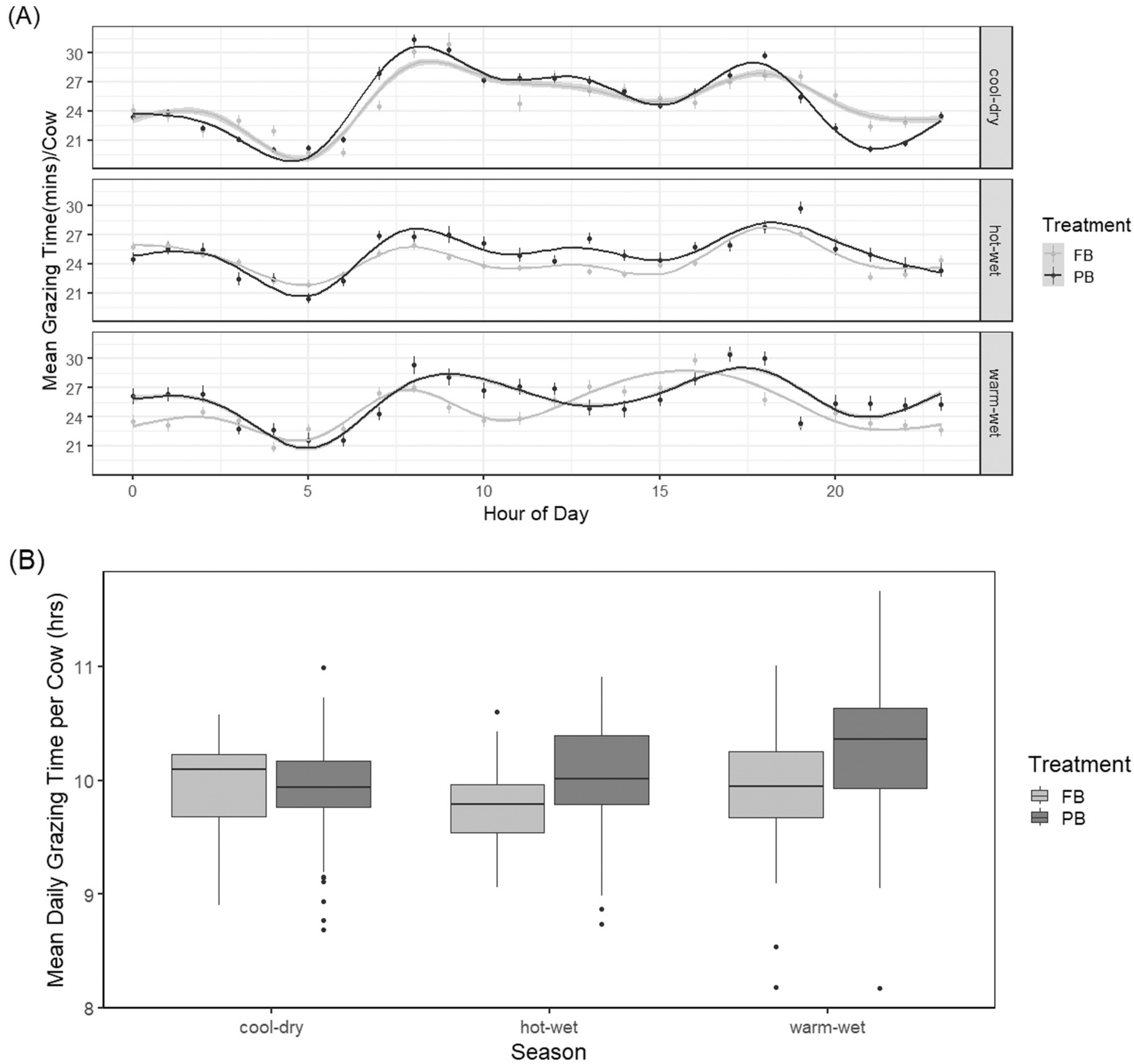

Fig. 4. (A). Observed compared to modeled circadian grazing patterns of cattle in patch burn and full burn treated pastures in 2017 in three different seasons. (B). Average grazing hours per day in patch-burn vs. full burn pastures in three different seasons.

Understanding how land management may affect temporal cattle grazing behavior is important because it is strongly linked to energy intake and nutrition (Gregorini et al., 2017). In temperate regions, cattle are known to engage in approximately four grazing bouts during the day with the longest grazing event during dusk (Gregorini et al., 2006). We detected 3–4 peaks in grazing including grazing at night in this subtropical humid grassland (Fig. 4a). The least time period of grazing was early in the morning between 3 – 6 am and the longest period of grazing was during the morning peaking at 8–9 am and in the evening around 6 pm. The results of our study on circadian grazing support the hypothesis that cattle graze less during times of heat stress, with grazing behavior reduced compared to peaks at dawn and dusk (Ehrenreich and Bjugstad, 1966). Similar to other studies in subtropical grasslands, our study showed fairly equal grazing time in the morning and dusk (Caram et al., 2021). Patterns of grazing coincided with temperature and our highest ranked model included both season and temperature covariates. This highest ranked model also included the covariate of fire treatment. Overall, it seems that cattle in PB grazed for longer than FB across many hourly periods of the day (Fig. 4a.). To assess this overall effect, we compressed grazing time to hours per day and found that cattle in PB treatments grazed significantly longer in warm-wet and hot-wet season (Fig. 4b). However, the difference is only a 3.7% and 2.7% increase in grazing time, respectively, and therefore may not be biologically significant. These small differences may be due to the presence of both higher quality forage and higher quantity forage in the patch-burn pastures and this heterogeneity may alter cattle grazing and searching strategies. Caram et al. (2021) showed that cattle may modify their grazing and searching strategies depending on pasture attributes, with morning grazing length dependent on crude protein availability and dusk grazing sessions depending more on herbage mass and allowance. It is interesting to note that in the cool-dry season, there were no differences in grazing time between FB and PB and this may be due to being immediately after fire occurred. Overall model fit of our top ranked model is low (R^2adj=0.26) suggesting many unknown factors driving timing of grazing. However, we believe the model provides important inference about circadian grazing patterns in humid, subtropical rangeland that draws awareness to the importance of pasture management in altering cattle behavior. Overall, of the factors we measured, only small changes in temporal grazing behavior were detected, and more detailed studies on how these small changes may or may not impact physiology and growth are needed.

In this one-year study, we have shown that patch-burn management influences grazing behavior. As new patches are burned and other patches increase in time-since-fire, the dynamics of grazing behavior may become more complex. A longer-term study is needed to understand how cattle grazing shifts when multiple types of burned patches are available, e.g. one, two, three years' time since fire, and if patch-burn grazing creates a shifting mosaic of ecosystem services in subtropical humid grazing lands. Future studies could also assess interactions of pasture-type and fire regime and focus on whether the carrying capacity of grasslands will change under patch-burn management. Ecosystem functions such as productivity, net greenhouse gas sink, habitat structure, plant diversity, and forage value, should be evaluated in patch-burned subtropical grasslands. Assessing synergies and tradeoffs of multiple ecosystem services resulting from patch-burn grazing management compared to typical full burn grazing management will be an important step prior to making management recommendations.

Funding

Funding provided by the National Institute of Food and Agriculture [grant number 2016–67019–24988 and 2021-67019-33431], the Alltech-Archbold Research Alliance, and a US Dept of Agriculture (USDA) cooperative agreement with Archbold for LTAR (58–0202–7–001) National Institute of Food and Agriculture NIFA Grant No. 2021-67019-33431.

CRediT authorship contribution statement

Elizabeth H. Boughton: Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization, Supervision. **Britt W. Smith:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Carl Bernacchi:** Writing – review & editing, Funding acquisition. **Nuria Gomez-Casanovas:** Writing – review & editing, Funding acquisition, Conceptualization. **Raoul K. Boughton:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jed Sparks:** Funding acquisition, Writing – review & editing. **Evan DeLucia:** Funding acquisition, Writing – review & editing. **Hilary M. Swain:** Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

Once the article is accepted for publication, data sets used will be published in the Environmental Data Initiative.

Acknowledgments

This research was a contribution from the Long-Term Agroecosystem Research (LTAR) network. LTAR is supported by the United States Department of Agriculture. Gene Lollis, Laurent Lollis, Kelsi Wirick, Mary Margaret Hardee, and Bethany Wight Penabade (deceased) assisted with cattle management and GPS collar data management. Buck Island Ranch researchers and cattle operations staff implemented prescribed fires.

Appendix 1. Five grazing periods for each fire treatment. Cattle were rotationally grazed between fire treatments. Animal use days were kept similar among treatments

Grazing Period	Treatment	Dates
1	Full Burn	March 27 – April 19, 2017
2	Full Burn	May 25 – July 25, 2017
3	Full Burn	Aug 25 - Sept 25, 2017
4	Full Burn	Oct 21 -Nov 21, 2017
5	Full Burn	Dec 11 – Dec 21, 2017
1	Patch Burn	Feb 7 - March 27, 2017
2	Patch Burn	April 19 - May 25, 2017
3	Patch Burn	July 25 - Aug 30, 2017
4	Patch Burn	Sept 27 - Oct 21, 2017
5	Patch Burn	Nov 21 - Dec 11, 2017

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