PATCH-BURNING IMPROVES FORAGE NUTRITIVE VALUE AND LIVESTOCK PERFORMANCE OVER ROTATIONAL AND CONTINUOUS GRAZING STRATEGIES

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Title

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

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ABSTRACT

Rangelands simultaneously support livestock production while maintaining ecosystem functionality. Patch-burning is a grazing management strategy with benefits for wildlife habitat and conservation. However, previous work pertaining to livestock has not examined potential benefits to livestock production. We assessed forage nutritive value, and cattle performance on patch-burning compared to continuous and rotational grazing. We also examined how prescribed fire alters forage mineral content through time since patch-burning. The recently burned patch had better forage nutritive value than patches with longer time since fire and no fire grazing methods, meeting the highest proportion of cow requirements. In 2017, a mild-drought year, cows performed better on patch-burned pastures. Without the mild-drought year, patch-burn cattle performance was similar to continuous, but better than rotational grazing. Mineral content varied seasonally, but was greater in recently burned patches than other patches. Our results indicate patch-burning can benefit livestock production while working to achieve rangeland conservation goals.

ACKNOWLEDGMENTS

There are several people who have helped to me reach this point, that I would like to thank for their guidance, commitment, patience and time. My first thank-you goes to Dr. Devan McGranahan. I thank you for the opportunity to work on this project, sharing your passion for prescribed fire with me, and guidance while navigating the universe of R. You have been more than willing to share your knowledge with me and I always walk away from our conversations learning something new. Thank you to Dr. Kevin Sedivec for the logistical support during my time at Streeter, always taking time out of your busy schedule for me and for showing me Perry Mason. I will be forever grateful for all the help you provided during my time at Streeter and NDSU. Thank you to Dr. Kendall Swanson for always being willing to discuss my new ideas, and reminiscing about Canada with me. Your guidance has helped me to expand my ruminant nutrition knowledge and integrate an animal science perspective into my work.

A big thank you goes out to everyone who helped collect data for this project. Without you this thesis would not exist. Dr. Marisol Berti allowed us to use her NIRS machine and lab space for our forage analysis. Her graduate students and technicians provided much need technical support for the NIRS machine. Micayla Lakey and her technicians collected all of the 2017 and 2018 data. Erin Gaugler and Megan Dornbusch collected much of the summer 2019 data. Naomi Hegwood, Paige Harman, Laura Smith, and Morgan Gallagher assisted with much of the forage clippings and spent many long hours grinding forage samples. I would also like to thank all of the full-time staff at Central Grasslands for all their assistance during my time at the station and making Streeter feel like my North Dakota home.

Being very far away from home while at graduate school, words barely describe how thankful I am for my fellow grad students, past and present while at NDSU. You have become a second family to me. Thank you for the help, support, conversations, and much needed laughs.

Lastly, I would like to thank my family. My parents and brother have always encouraged and supported my interest in agriculture even though it has meant travelling first to another province and now another country. Finally, thank you to my partner Josh for always believing in me. Without your encouragement I would have never achieved this.

DEDICATION

I would like to dedicate this thesis to Kara McGonigle who fostered my interest in rangelands many years ago.

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Abstract

Rangeland management needs to consider environmental and production sustainability to maximize land manager adoption. While conservation benefits of heterogeneity achieved through patch-burn grazing have been well established, patch-burn grazing has been less studied from a livestock production standpoint. To determine how patch-burning impacts livestock production, we compared temporal and spatial trends in forage nutritive value and livestock performance on patch-burn grazing to other grazing management strategies like rotational grazing, and continuous grazing. We measured forage nutritive value across pastures managed with patch-burn, continuous, and rotational grazing monthly during the 2017-2020 grazing seasons. Using multivariate analysis of NIR-derived data, we reduced several forage variables into a single Forage Composition Index, which was used as a dependent variable in univariate models. To determine grazer space use, we counted fecal pats around each forage sample point. We weighed cows before and after the grazing season to assess livestock performance for each grazing strategy. Burning increased crude protein, neutral detergent fiber digestibility, and energy, and decreased acid detergent fiber, neutral detergent fiber, and lignin components of forage nutritive value in recently-burned patches relative to unburned patches and grazing strategies without fire. While many components followed seasonal trends, the recently burned patch had the best forage nutritive value throughout the grazing season. Cows spent more time in recently-burned patches compared to other patches in pastures managed with patch-burning. Patch-burning created heterogeneity in forage nutritive value and grazer selection throughout the duration of the study. Recently-burned patches had the highest proportion of forage sampling points that met grazing cow requirements throughout the grazing season. As such, cows from patch-burned pastures performed better over the course of the grazing season. Patch-burn grazing can benefit livestock production and performance while creating heterogeneity necessary to achieve rangeland conservation goals. Patch-burning pastures resulted in best meeting the nutritional requirements of grazing cattle and resulted in better weight gains on patch-burning pastures.

Introduction

Rangeland ecosystems are often working landscapes managed to meet livestock production and conservation objectives (Butsic et al., 2020). At times, land managers might prioritize one of these objectives over the other (Dunn et al., 2010). When livestock production is the primary goal in land management, the conventional approach is to use grazing strategies that promote homogeneous grazer distribution and biomass removal (Holechek et al., 2010). Conventional grazing strategies, reduce grazer selectivity to promote even forage use, which in turn creates pasture level homogeneous vegetation structure (Briske et al., 2008).

But rangelands are inherently heterogenous systems, and conventional, homogeneity-based management practices reduce the value of working landscapes for biodiversity. Prior to European settlement, rangelands worldwide were characterized by a shifting mosaic of diverse patch types driven by the fire-grazing interaction. However, alterations to pre-colonial fire regimes and uniform grazing management have homogenized vegetation structure, which supports a narrow suite of biodiversity (Fuhlendorf et al., 2017). Managers can increase heterogeneity, through spatially-discrete management that creates a mosaic of patches that vary in structure and composition (McGranahan et al., 2012, 2013; Winter et al., 2012). For example, patch-burn grazing is a heterogeneity-based management that aims to replicate the shifting mosaic of pre-settlement vegetation patterns with spatially-patchy prescribed fire and livestock grazing (Fuhlendorf & Engle, 2004). Conversely, conventional grazing management narrows the range of available niches by reducing diversity in vegetation structure (Fuhlendorf et al., 2009).

Heterogeneity based management strategies have focused on conservation, and only sought to show that livestock production will not be negatively affected (e.g., Limb et al., 2011). But there is some evidence that patch-burn grazing might provide direct benefits for livestock production. Patch-burning produces high-protein forage regrowth, which attracts livestock and concentrates grazing in these areas, creating contrast between patches with varying time since fire (Leonard et al., 2010; Wallace & Crosthwaite, 2005). Patch contrast stabilizes pasture level temporal forage availability which can act as a ‘grass bank’ during periods of drought, maintaining livestock production (Allred et al., 2014; McGranahan et al., 2014; McGranahan et al., 2016; Spiess et al., 2020). Patch-burning also increases concentration of some minerals in post-fire regrowth, which might have benefits to livestock nutrition (Wanchuk et al., 2021). Continuous and rotational management strategies have been found to have similarly low levels of forage re-grazing at a moderate stocking rate (Porensky et al., 2021). However, re-visitation of forage in patch-burning and attraction to grazing hotspots post fire has not been examined. While rotational grazing has also been used to attempt to create structural heterogeneity without the use of fire (Milligan et al., 2020), it has yet to be determined whether such management has the same potential benefits to livestock production without fire.

In addition to driving the fire-grazing interaction, fire-enhanced forage nutritive value provides ecological benefits and enhances livestock production. Crude protein has been widely shown to increase in response to fire and grazing (Allred et al., 2011; Powell et al., 2018;

Sensenig et al., 2010). However, a more complete picture of forage composition, at frequent intervals through the grazing season, is required to understand how livestock nutrition and production is impacted by management (Scasta et al., 2016). Chemical composition and digestibility of rangeland forage are often used as an indicator of forage quality, and includes components such as crude protein, acid detergent fiber, lignin, and neutral detergent fiber (Rouquette, 2016). Forage nutritional composition has direct impacts on livestock performance as it defines the maximum limits for livestock weight gains, and influences reproductive success (Sollenberger & Vanzant, 2011).

Nutritional content of forage on rangelands can have great temporal variability over the grazing season and across grazing strategies. Forage quality generally declines as the grazing season progresses due to plants maturing and developing a greater proportion of fibrous, structural cell components (Arzani et al., 2004). However, factors such as weather and management can affect the rate of forage quality decline, altering quality trends (Milchunas et al., 1995). Because temporal patterns of forage nutritive content are variable, it is important to monitor whether a forage base is able to meet nutrient requirements throughout the grazing season.

We determine if heterogeneity created through patch-burn grazing will affect temporal and spatial trends in forage nutritive value, and subsequently improve cow weight gains. There has yet to be a comprehensive examination of forage nutritive composition in patch-burn grazing sampled across frequent intervals in the grazing season and compared against other conventional and non-conventional grazing management strategies. More generally, few patch-burn grazing studies have been conducted in the northern Great Plains, and those only report crude protein (Powell et al., 2018; Spiess et al., 2020). Here, we compare continuous and rotational grazing strategies to patch-burn grazing with the following objectives: 1) describe the general temporal trends in forage nutritive composition across three grazing strategies; 2) examine the relationship between forage nutritive value and selection by grazing livestock across different grazing strategies; 3) ascertain, at monthly intervals, which strategies best meet cow nutritional requirements, and how cow performance varies among strategies. We hypothesized that burned patches in patch-burn grazing will have superior forage nutritive composition and provide more forage that meets grazing nutrition requirements throughout the entire grazing season. We also expect spatial patterns in forage composition to drive patterns in grazing and livestock performance, with cattle on patch-burned pastures concentrating in recently-burned patches, resulting in heterogeneity in forage composition and grazer selection under patch-burning. Finally, we expect that recently burned patches in patch-burning to be superior in forage nutrient value inducing higher season-long cow weight gains.

Methods

Study Location

We conducted this study at the North Dakota State University Central Grasslands Research Extension Center (CGREC) in Stutsman and Kidder counties near Streeter in south-central North Dakota, USA (46°45’N, 99°28’W). The study site is located in the Missouri Coteau ecoregion and pasture vegetation is characterized as mixed-grass prairie. Climate at CGREC is characterized as temperate. The Center has a mean growing season precipitation of 361mm with growing season temperature ranging from 12 °C to 21 °C (National Weather Service, 2021). The 20-year mean annual precipitation is 504 mm (National Weather Service, 2021).

Plant communities are comprised of native and introduced C_3 grasses, native C_4 grasses, forbs, legumes, and shrubs. Herbaceous cover includes Kentucky bluegrass (*Poa pratensis* L.), smooth brome (*Bromus inermis* L.), western wheatgrass (*Pascopyron smithii* [Rydb] À. Löve), green needlegrass (*Nassella viridula* [Trin.] Barkworth), blue grama *(Bouteloua gracilis* [Willd. ex Kunth] Lag. ex Griffiths), little bluestem (*Schizachyrium scoparium* [Michx] Nash, goldenrods (*Solidago* spp.), silverleaf scurfpea (*Pediomelum argophyllum* [Pursh] J. Grimes), and leadplant (*Amorpha canescens* Pursh) (Limb et al., 2018). Western snowberry (*Symphoricarpos occidentalis* [L.] S. F. Blake) is the dominant woody species.

Study Design

The experimental design and animal management were approved by the North Dakota State University Institutional Animal Care and Use Committee (IACUC A20033). Grazing strategies consisted of three different management strategies, each replicated four times, for a total of 12 study pastures, each approximately 65 ha. The patch-burned grazing strategy consisted of a pasture in which one-quarter (approximately 16 ha) was burned each spring, followed by season-long cattle grazing without interior fences. The two no-fire grazing management strategies consisted of season-long, continuous grazing; and a four-paddock modified twice-over rest rotation grazing system. All pastures were stocked with commercial crossbred Angus cow-calf pairs (*Bos taurus*) and grazed from mid-May to mid/late-October at a stocking rate of 0.5-0.6 ha AMU^{-1}.

Grazing strategies were applied annually from 2017-2020, although the rotational system was added in 2018. Data were collected from the patch-burn and continuous grazing pastures each of the four years, while the rotational grazing system only provides three years of data.

The rotational grazing system was a hybrid system of the twice-over rotation (Biondini & Manske, 1996; Sedivec & Barker, 1991) and rest rotation grazing system (Hormay & Talbot, 1961) used throughout the northern Great Plains. The modified twice-over rest-rotation grazing system was modified to target structural heterogeneity between grazing paddocks similar to that created in the patch-burn grazing. At the beginning of each grazing season, each paddock was assigned to one of four target grazing intensities: heavy use (>60% aboveground herbaceous disappearance), full use (40% to 60% disappearance), moderate use (20% to 40% disappearance), and rested (no grazing in that season). These different intensities aim to create structural heterogeneity similar to patch-burn grazing. Cattle rotated twice within each pasture (35% of the grazing days in the first rotation, 65% of the grazing days in the second rotation) throughout the grazing season for a total of 74, 54, 27 days on the heavy use, full use, and moderate use paddocks, respectively. The grazing intensity of each paddock is rotated each year so that each paddock receives each of the four grazing intensities once over a four-year period. Thus, heavy use pastures transitioned to rested, full use to heavy use, moderate to full use, and rested to moderate use during the four-year cycle.

Forage Sampling and Analysis

To compare spatial and temporal forage component composition across grazing strategies, forage was clipped around randomly selected fixed points that were returned to at each sampling period throughout the grazing season each year. The randomly selected fixed points captured all time-since-fire patches and time since every grazing intensity on the rotation (Appendix A). Sampling locations were distributed across major ecological sites in each pasture and visited every month from cattle turnout to removal.

Above ground biomass was clipped from a 25 x25 cm frame to determine forage nutritive value during the grazing season. Clipping was design to represent forage quality at the feeding station level, or the area available for animals to graze without walking (WallisDeVries et al., 1998). All plant material above the crown was clipped to minimize contamination from soil and litter, but still include the live and standing dead material. At the time of clipping, fecal pats were counted within a five-meter radius of clipping points to passively determine grazer space use. Fresh, individual fecal events were counted as a fecal pat to avoid recounting or overcounting. After clipping, we dried forage samples for 48 hours at a temperature of 60^{o}C and then ground with a Wiley Mill (Model 4, Thomas Scientific, Swedesboro, New Jersey) using a 1-mm screen.

Ground samples were analyzed using near-infrared spectroscopy (NIRS) to determine chemical composition using an XDS-NIRS rapid content analyzer (FOSS Analytical, Hillerød, Denmark) and WIN ISI scan software version 4.10.015326 (Infrasoft International LLC., State College, Pennsylvania). We scanned samples over a wavelength spectrum of 400–2498 nm at a spectral resolution of two millimeters. A subsample was determined by the NIRSS software and sent for wet-chemistry analysis at the North Dakota State University Animal Sciences laboratory to determine actual chemical composition. With the wet chemistry data, the WIN ISI software developed and validated a calibration equation. Values were determined for acid detergent fiber (ADF), neutral detergent fiber, crude protein, 24-hour NDF digestibility, and acid detergent lignin (lignin) using the created calibration equation. To estimate energy content of samples, net energy for maintenance (NE_m) for cattle was estimated from acid detergent fiber as follows (NASEM, 2016; NRC,2001):

$$DE = 3.44-(0.022*ADF) \text{ (Eq. 1)}$$

$$ME = (DE*0.82) \text{ (Eq. 2)}$$

$$NE_m = ((1.37*ME)- (0.138*ME^2) + (0.0105*ME^3) - 1.12)) \text{ (Eq. 3)}$$

Values for nutritional requirements were determined based on a 572 kg March-April calving cow with 8 kg/day peak milk production and births a 40 kg calf for a mid-May to mid/late-October grazing season (~155 days; NASEM, 2016).

Livestock Data Collection

Data collection took place during the 2017-2020 grazing seasons. Cattle were sorted into pastures based on weight to maintain consistent stocking rates and average cow weight across pastures. Cows were weighed on two consecutive days before turnout. Following removal from the pastures, cows were weighed for two consecutive days once again. With these weights average daily gain (ADG) was calculated for each individual COW by subtracting the average turnout weight from the average final weight then dividing by the number of days spent grazing.

Data Analysis

All analysis was completed in the R statistical environment (R Core Team, 2019). To determine differences in forage nutrient concentrations, we compared time since fire and grazing strategy across all forage quality parameters with a generalized linear mixed-effects regression model (GLMM). We created a GLMM using glmmTMB function in the glmmTMB package for R statistical environment using beta family (Brooks et al., 2017). Pasture, year, and month were included as a nested random-effect term along with ecological site, to account for any spatial and temporal interactions caused by repeated sampling measures in the study design. We used Tukey post-hoc comparisons with the glht function from the multcomp package to compare grazing strategies (Hothorn et al., 2008).

To determine dissimilarity across a time since fire gradient we used principal component analysis (PCA) from the vegan package (Oksanen et al., 2016). Prior to PCA, all forage nutrient components were scaled. We did not use net energy for maintenance in the PCA since it was a calculated value. To compare differences between time since fire, grazing strategy, and years, we conducted post-hoc pairwise comparisons using pairwise.factorfit from the RVAideMemoire package (permutations = 199). We used the first PCA axis site scores to create a new variable for subsequent analysis (Morales & Beal, 2006), forage composition indicator which served as a comprehensive indicator of forage composition. This allowed us to consider all aspects of forage composition for further analysis, rather than just using crude protein as an indicator of forage nutritive value.

To compare cattle grazing preference to forage quality, we used fecal pats around each forage sampling point to determine a selectivity index based on the calculations described in Powell et al. (2018). Selectivity index values above 1 indicate preference for a patch. We then tested the fecal pat counts against forage composition indicator and grazing strategy GLME models in glmmTMB using a zero-truncated negative binomial distribution. Because there were several zero fecal pat counts, we used zero inflation for the models set identical to the conditional effects' formula. Based on the models, we determined predicted fecal pat counts for grazing strategy and forage composition indicator using the ggpredict function in ggeffects package (Lüdecke, 2018).

We also tested variability of forage composition indicator and fecal pat counts in patch-burning and continuous grazing to determine heterogeneity in forage nutrient composition and grazer space use. We calculated the standard deviation of each individual point over the duration of the study, then calculated mean and standard error for each grazing strategy.

To determine differences between livestock performance across grazing strategy, we compared cow ADG between grazing strategies using linear mixed-effect models using lmer from the lme4 package (Bates et al., 2015). We used pasture and year nested together, and individual cow as random effects, with grazing strategy as the fixed effect. We used the mutlcomp package function glht to compare grazing strategies post-hoc (Hothorn et al., 2008). For all models and tests $\alpha \leq 0.05$ was considered significant.

Results

Nutritive composition in burn patches of patch-burn pastures was different than patches with longer time since fire and no-fire grazing strategies (Figure 1.1). For the rotational grazing system, there was generally no difference between grazing intensities, with the exception of crude protein and neutral detergent fiber digestibility (Appendix B). Crude protein was lower in the rested and all other grazing intensities (χ^2=3763, p<0.001), but when compared to the patch-burn patches, there was no difference between heavy, full, moderate, and rested intensities and the 1 year since fire, 2-3 years since fire, and unburned patches. Neutral detergent fiber digestibility was significantly lower in the heavy and full intensities than the moderate and rested intensities (χ^2=1365.9, p<0.001). However, once again when compared to the patch-burn patches, there was no difference between heavy, full, moderate, and rested intensities and the 1 year since fire, 2-3 years since fire, and unburned patches. Therefore, we did not separate the rotational system by intensity in subsequent analyses or any figures. Crude protein was highest (χ^2=6134.7, p<0.001) in the recently burn patches relative to other patches throughout the majority of the grazing season. Seasonality trends were evident across all time since fire gradients and grazing strategies, with crude protein decreasing as maturity advances. Recently burned patches had lower amounts of acid detergent fiber (χ^2=2710.9, p<0.001) and neutral detergent fiber (χ^2=1646.4, p<0.001) compared to other patches and grazing strategies. In May, acid and neutral detergent fiber content in one year since fire patches was similar to the recently burned patches, but increased as the grazing season progressed. In recently burned patches, acid and neutral detergent fiber content remained relatively stable throughout the grazing season. Lignin content was lower in recently burned patches (χ^2=27976, p<0.001) compared to longer time since fire patches, but not different than no fire grazing strategies. The net energy for maintenance content of recently burned patches was greater than longer time since fire patches and no fire strategies (χ^2=12533.9, p<0.001). Recently burned patches remained constant after an initial decline between May and June, but patches with longer time since fire, continuous grazing, and rotational grazing declined throughout the grazing season. All patch-burning patches, and no fire grazing strategies declined in neutral detergent fiber digestibility as the grazing season progressed, but recently burned patches had less of a decline and remained greater than all other patches, continuous, and rotational grazing (χ^2=982.66, p<0.001).

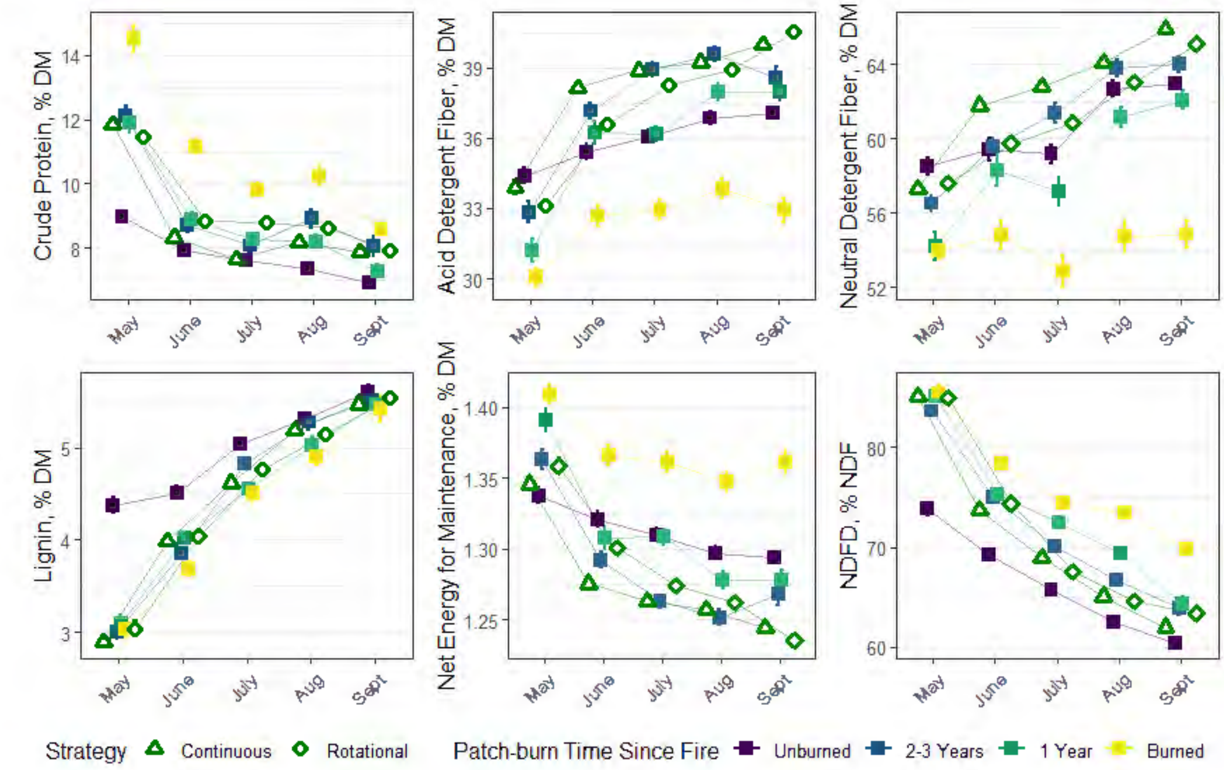

Figure 1.1. Mean and standard error of each forage nutrient component across the patch-burn time since fire gradient and the continuous and rotational no fire strategies. Patch-burn grazing has been split by time since fire. Lines connect each grazing strategy or time since fire across months. NDFD, %NDF: Neutral detergent fiber digestibility as percent of neutral detergent fiber.

Forage nutrient content was different between patches with varying time since fire and no fire strategies. Distinct clusters of time since fire groups are seen in the PCA (Figure 1.2). Recently burned patches were associated with crude protein and net energy for maintenance, the unburned patches were most associated with lignin content and no fire patches most associated with acid and neutral detergent fibers. The 1 year and 2-3 years since fire transition patches fall in between the recently burned, unburned and no fire patches. The first PCA axis explained 63% of the variation (Eigen value = 3.17) and the second PCA axis explained 18% of variation (Eigen value= 0.89). Time since fire was correlated with forage nutrient content ($p<0.05$), but year, ESD, and grazing strategy (patch-burn, continuous and rotational) were not correlated ($p> 0.05$). Based on pairwise comparisons, the 2 year since fire and 3 year since fire patches were similar (p>0.05), therefore the 2 year since fire and 3 year since fire patches were grouped together as a transition patch. All other patches were different (p<0.05) from each other. Because of the location of the species scores, when the first PCA axis site scores are used to create the forage composition indicator, higher forage composition indicator values indicate more crude protein and neutral detergent fiber digestibility, and lower acid detergent fiber, neutral detergent fiber, and lignin.

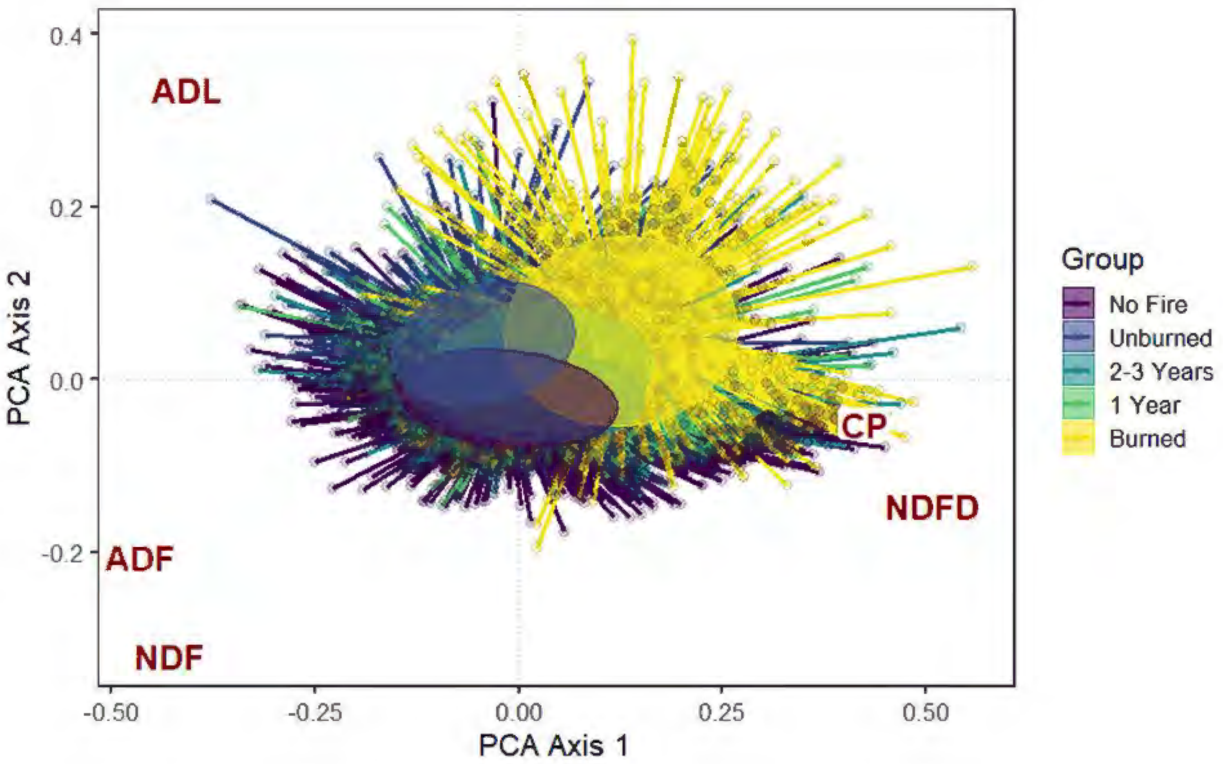

Figure 1.2. Principal components analysis (PCA) scatterplot based on forage nutrient components determined through near infrared spectroscopy. The no fire group includes continuous and rotational grazing. ADL: lignin, ADF: acid detergent fiber, NDF: neutral detergent fiber, CP: crude protein, NDFD: neutral detergent fiber digestibility. Site scores from the PCA axis 1 were used to create the forage composition indicator, which is a comprehensive indicator of forage nutritive value by combining several variables into one and used for subsequent analysis. Higher values of forage composition indicator have more crude protein and neutral detergent fiber digestibility, and lower acid detergent fiber, neutral detergent fiber and lignin.

Differences in grazer preference between patches and grazing strategies were evident (Figure 1.3a). While most time since fire patches are similar in May, livestock preferred the recently burned patches from June to August as indicated by selection values above one (Powell et al., 2018). Preference for recently burned patches declined in September, but was still preferred by cattle. One year since fire patches were also preferred by grazers in August and September over patches with longer time since fire. Within the patch-burn strategy, unburned patches were never preferred by grazers, and two-three years since fire patches were not preferred by grazers in July-September (Figure 1.3a). The rotational and continuous grazing strategies had a selection index average around one, along with a small error indicating no preference across forage collection points (Figure 1.3b; Powell et al., 2018). Selection for higher quality forage occurred in all three grazing strategies based on forage composition indicator and predicted fecal counts (Figure 1.3c). The predicted fecal count line for the rotational system has a higher intercept than the continuous or patch-burn grazing strategies, indicating that there were more fecal pats in any given spot by nature of the higher stock density and limited grazing area in the rotational paddocks. The continuous and rotational grazing strategies had lower forage composition indicator values than patch-burning, and therefore lower forage nutritive value, as designated by the horizontal boxplots. All grazing strategies have a similar rate of change on the predicted fecal count line, however, the upper limits of the line are limited by highest available forage composition indicator.

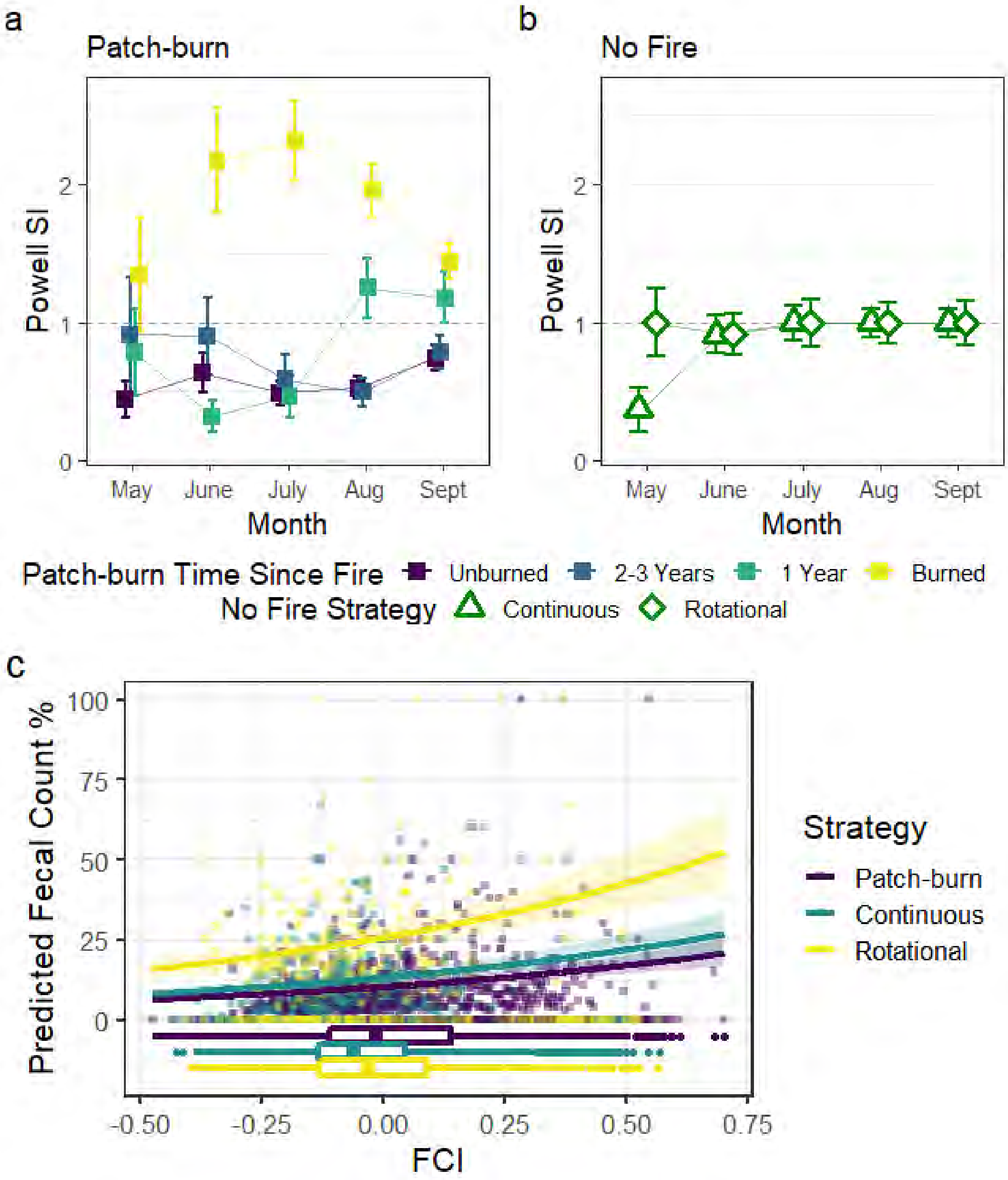

Figure 1.3. Cattle space use by month and compared to forage composition indicator for each grazing strategy. The top two plots show cattle space use calculated by using the Powell selection index for all the patch-burn time since fire patches (a), and the continuous and rotational no fire strategies (b). Selectivity values above 1 indicate a preference for the patch (Powell et al., 2018). The bottom plot (c) shows predicted fecal pat count for each sampling point as a percentage of total fecal pat counts for each pasture (Y axis) plotted against forage composition indicator which is derived from the first PCA axis (FCI; X axis). Lines indicate predicted trends in fecal pat counts as forage composition indicator increases. Points in the background indicate actual sampling points. Horizontal box and whiskers at the bottom of the plot indicates average forage composition indicator for each of the grazing strategies, with higher values indicating better forage nutritive quality.

Forage composition indicator of each point had more annual variability in patch-burn grazing than continuous grazing (Figure 1.4). Fecal pat count response was also similar, with the patch-burning producing more annual variability grazer for each point.

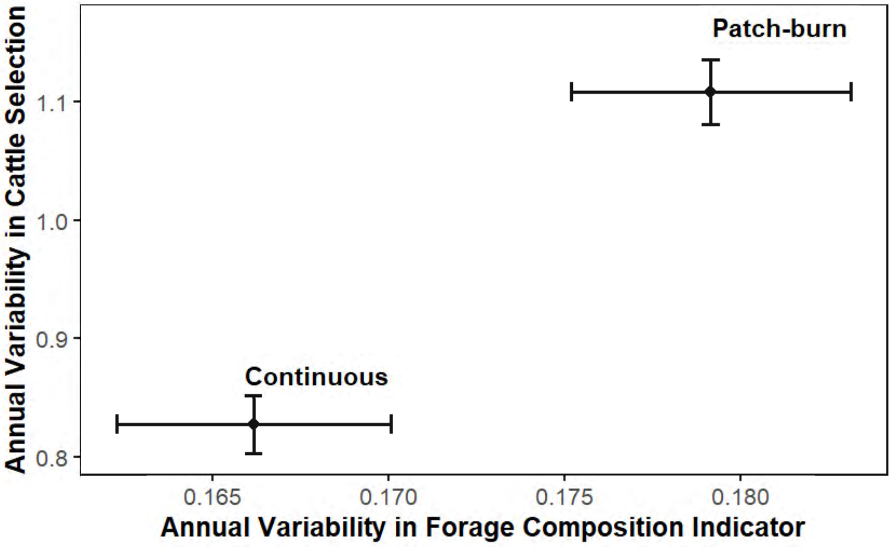

Figure 1.4. Annual variability in cattle selection and forage composition indicator for each sampling point by grazing strategy. Horizontal error bars represent variability in forage composition indicator while the vertical lines represent variability in cattle selection.

Cow average daily gain (ADG) was different between grazing strategies (χ^2= 8.92, *p*=0.012, Figure 1.5). Patch-burn ADG was different than the continuous and rotational strategies (patch-burn- continuous: Z= 2.44, *p*=0.039; patch-burn- continuous: Z= 2.66, *p*=0.022). Patch-burning ADG was different from zero (Z= 1.55, *p*=0.32), with cows gaining weight during the grazing season. The confidence intervals for continuous (Z= 5.00, *p*<0.001) and rotational strategies (Z= 0.84, *p*=0.79) were not different from zero, indicating that in general, by the end of the grazing season cows had only maintained their turnout weight.

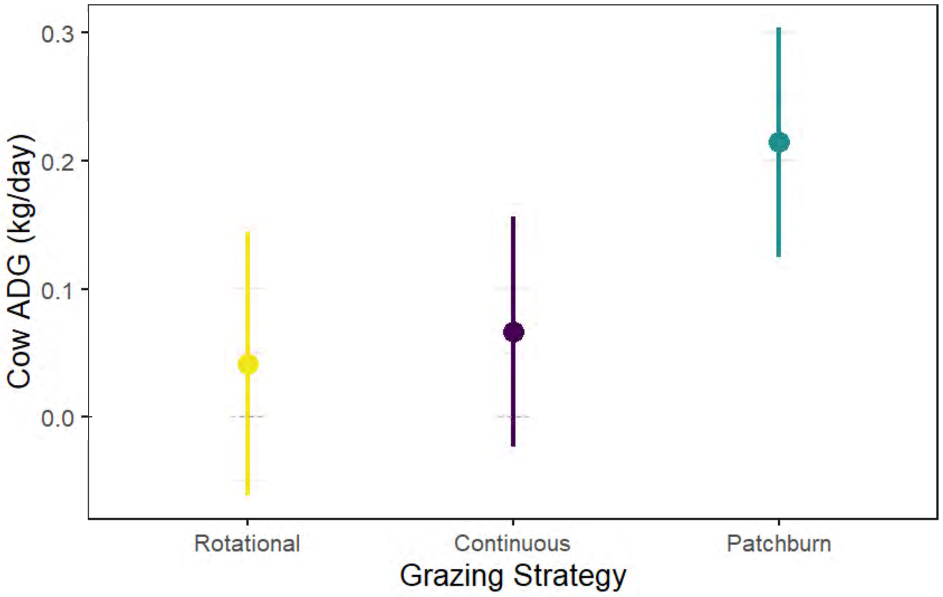

Figure 1.5. Average daily gain (kg/day) for cows in each of the grazing strategies. Points indicate the parameter estimate for average daily gain with 95% confidence intervals. The grey dashed line indicates zero, or no change in weight gain. Area above the line indicates an increase in weight during the duration of the grazing season and area below a decrease in weight.

A higher proportion of forage samples met or exceeded lactating cow requirements for net energy for maintenance and crude protein in the recently burned patches than all other patches with one or more years since fire, continuous, and rotational grazing (Figure 1.6). July had the lowest proportion of points that met requirements in recently burned patches, while all other patches had the lowest proportion of forage that met requirements in June.

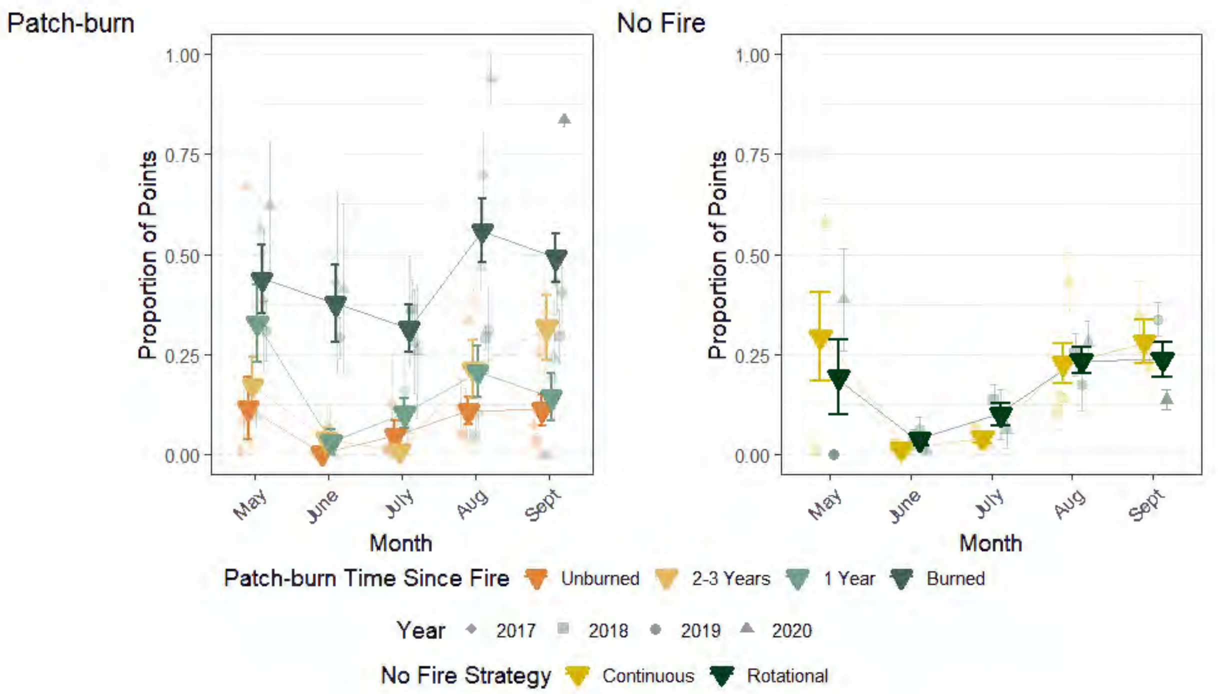

Figure 1.6. Mean proportion of points in each pasture that meet or exceed cow crude protein and net energy for maintenance requirements each month. The left figure is the patch-burning split by time since fire patches, while the right figure is the no fire strategies (continuous and rotational). Points in the background indicate the mean for each year. A proportion of 0 indicates that no points have met requirements. Requirements are based on NASEM, 2016, Nutrient Requirements of Beef Cattle for a 572 kg cow with 8 kg/day peak milk production and 40 kg calf birth weight. Net energy for maintenance was calculated from acid detergent fiber using Equations 1-3.

Discussion

We determined if patch-burning is beneficial for livestock by comparing temporal and spatial trends in forage nutritive value, and subsequent livestock weight performance to continuous and rotational grazing. Our results indicate there are benefits of heterogeneity achieved through patch-burning to forage nutritive value and livestock performance. Patch-burning, in comparison to non-fire grazing strategies, provided patches with higher nutritive value forage to best meet the needs of grazing livestock throughout the summer grazing season. As a result, lactating cows gained more weight on patch-burning pastures compared to the continuous and rotational grazing pastures.

Combining all forage nutrient components into the forage composition indicator provides a great deal of information on forage nutritive value to better gauge forage value than using a single nutrient component alone. Forage nutritive value increases are a fundamental driver of benefits seen under patch-burning that are not created under other grazing management strategies. Prescribed fire increased crude protein, net energy for maintenance, and neutral detergent fiber digestibility in the most recently-burned patches. Conversely, acid detergent fiber and neutral detergent fiber—which are attributable to the fibrous plant components that decrease intake and digestibility— were lowest in recently burned patches. Previous literature has also found increases in forage crude protein after fire (Allred et al., 2011; Dufek et al., 2014; Eby et al., 2014; Gullap et al., 2018; Mbatha & Ward, 2010; Powell et al., 2018; Raynor et al., 2015; Sensenig et al., 2010). While fewer studies have examined fire effects on acid detergent fiber and neutral detergent fiber concentrations than other forage components, these studies have also found a decrease with fire (Dufek et al., 2014; Gullap et al., 2018; Sensenig et al., 2010; Vermeire et al., 2020). Similar to another study, lignin content in recently burned patches increased as the grazing season progressed and was comparable to other grazing strategies (Raynor et al., 2015). Prescribed fire improves both palatability and forage nutritive value over grazing alone through increased leaf: stem ratios; younger plant tissue age, particularly in stems; and concentration of nutrients within less plant biomass (Van de Vijver et al., 1999; Vermeire et al., 2020).

Within-season forage nutritive value trends are an important consideration for livestock performance. Seasonal declines were evident across all patches and grazing strategies for crude protein, lignin, and neutral detergent fiber digestibility. However, acid detergent fiber and neutral detergent fiber did not follow these same seasonality trends, but rather remained fairly constant in recently burned patches throughout the grazing season. While fire initially improves forage composition, our study and previous research indicates subsequent grazing is required to maintain plants in an immature stage and prevent diminished forage value as plants mature through the growing season (Allred et al., 2011; Dufek et al., 2014; Mbatha & Ward, 2010; Powell et al., 2018; Raynor et al., 2016; Van de Vijver et al., 1999; Vermeire et al., 2020). The timing of forage maturity has a large impact on forage nutritive value which strongly impacts cattle performance, regardless of grazing strategy (Kearney et al., 2022). It is important to note that mature cow requirements decline as the grazing season progresses and cows reach mid to late lactation, similar to the forage quality trends (Adams et al., 1996). However, for cattle to gain weight, they need to be consuming forage that exceeds minimum requirements (NASEM, 2016), which is what we see in patch-burning.

Patch-burning created temporal patterns of heterogeneity in forage nutritive value and fecal counts. We found cattle selection at each point varied with time since fire, following nutrient value trends. Previous research found that stocking rates are more important than grazing strategy for determining grazing patterns (Porensky et al., 2021). In rotational and continuous grazing at moderate stocking rates, the majority of plants are never grazed, with a small portion of the grazed plants being re-grazed (Porensky et al., 2021). However, we found in patch-burning that cattle returned to recently burned patches until a new recently-burned patch was created. In South Africa, where ‘grazing lawn’ plant communities exist, livestock return to these areas several times throughout the grazing season due to high nutritive value forage, similar to our results with patch-burning (Grant et al., 2019).

Grazer preference fluctuated based on spatial and temporal patterns of forage nutritive value across grazing strategies. Cattle showed a preference for areas that had high forage nutritive value in all grazing strategies, as expected (Ganskopp & Bohnert, 2009; Raynor et al., 2016; Sensenig et al., 2010). In the patch-burning pastures, cattle generally preferred recently-burned patches over all other areas, consistent with fire-grazing interaction research done elsewhere (Allred et al., 2011; Powell et al., 2018; Raynor et al., 2015; Sensenig et al., 2010). Our measurement of multiple forage value components at multiple points within the grazing season offers a more nuanced understanding of how grazing strategies meet dynamic cattle nutrition needs. For example, large ruminant grazers must supplement their use of areas with high crude protein, where plant biomass is typically low, and areas of high acid detergent fiber and biomass to fill their rumens and efficiently meet requirements (Grant et al., 2019; Sensenig et al., 2010). As calves gain weight and independence from their mothers, their shift towards independent grazing also occurs, putting a greater demand on forage availability (Boggs et al., 1980). So, while cattle might prefer recently burned patches for their palatability and high protein content, cattle did shift their grazing to the previous year's burned patches towards the end of each grazing season (Figure 1.3a).

Patch-burn grazing has created a broad gradient of forage nutritive indicator values between different time since fire patches that was not seen in the other grazing strategies. Many other patch-burning studies have used crude protein or fiber content as a measure for forage quality when examining how heterogeneity in forage composition interacts with grazer selection (Allred et al., 2014; Powell et al., 2018; Raynor et al., 2016; Sensenig et al., 2010). However, grazers simultaneously respond to several forage nutritive characteristics when selecting feeding stations (Ganskopp & Bohnert, 2009). We used a range of forage nutritive characteristics, which provides evidence that forage in patch-burning better met requirements, enhancing livestock production through livestock gains.

Patch-burning seeks to override selectivity on a finer feeding station scale by homogenizing forage quality and using this to attract livestock to a desired grazing area. In contrast, rotational strategies seek to override inherent heterogeneity and livestock selectivity at the pasture scale by manipulating grazing intensity through stocking density, grazing duration and fencing (Venter et al., 2019). The goal with these systems is often to maximize herd-level gains through increased stocking rates, rather than increasing individual gains or bite-level quality (Jones & Sandland, 1974). In continuous grazing strategies, grazing hotspots are established based on patterns of inherent heterogeneity in pastures, such as distance to water, topography and forage quality (Ganskopp & Bohnert, 2009; Grant et al., 2019). These areas continually get grazed, which prevents plants from reaching maturity, which in turn creates high-quality forage in these hotspot areas that can persist for several grazing seasons (Ganskopp & Bohnert, 2009; Pavlů et al., 2006).

Meeting the nutritional requirements of grazing livestock is essential to producing weight gains and maintaining productivity. Recently burned patches had the greatest proportion of points that met the requirements of the cattle grazing throughout the grazing season, compared to the longer time since fire patches and grazing strategies (Figure 1.6). When forage quantity is adequate to meet grazer intake, forage nutritive composition is the limiting factor in livestock average daily gains (Sollenberger & Vanzant, 2011). Cattle gained weight on the patch-burning pastures throughout the grazing season and during all years, while cattle in other grazing strategies without fire did not consistently gain weight throughout the grazing season, providing further evidence that nutrient requirements are more adequately being met on patch-burning. Patch-burn grazing has produced similar or increased weight gains in stocker animals and cows with calf at side to continuous grazing or homogeneous fire management during average precipitation years (Farney et al., 2017; Limb et al., 2011; Scasta et al., 2016). During drought when both forage quantity and nutritive value are likely to be limiting, livestock weight gains are increased under patch-burning management (Scasta et al., 2016; Spiess et al., 2020).

There are some caveats of our study design regarding hand clipping and drivers of higher forage nutritive value. Our forage nutritive values are based on clipped samples meant to represent what is available to a cow at the scale of a feeding station, but does not reflect exactly what she consumes. However, comparisons of consumed forage sampled via rumen extrusa against hand-clipping from the feeding station have produced similar estimations of forage crude protein (Gindri et al., 2019). While fire and grazing disturbances can alter vegetation, there is no indication that changes in forage nutritive composition from patch-burning are due to changes in plant community composition. Generally speaking, phenology, climatic factors, and geographical location provide more variation in nutritive content of functional groups than the specific species or morphology (Lee, 2018). Several previous studies have found that there are no major changes to plant functional groups with patch-burning (Powell et al., 2018; Vermeire et al., 2020).

Our results inform land managers on grazing practices for conservation management for both private commercial rangelands as well as the millions of acres of public lands in the northern Great Plains and beyond. The question of best grazing management strategies to balance conservation and livestock management is a global issue (O'Connor et al., 2010; Richardson et al., 2014). There has also been considerable debate over whether spatial heterogeneity and other benefits of fire can be achieved through grazing management alone (McNew et al., 2015; Vermeire et al., 2020). Our results suggest that benefits to livestock performance and forage nutritive value fall short in the grazing strategies without fire, including the rotational grazing system designed to create heterogeneity without fire.

While there currently is minimal use of fire on private lands in the northern Great Plain (Bendel et al., 2020), fire has been used extensively for wildlife management in the area (Dixon et al., 2019). Recent studies in the northern Great Plains have found no negative impacts from fire and grazing on forage productivity and plant community composition (Gates et al., 2017; Kral-O'Brien et al., 2019). Our results further build on the merits of patch-burning for producers in this area and beyond. While fire management on private land is currently limited in the northern Great Plains, landowners in areas of the southern areas of the Great Plains have been using fire as a management tool to improve grassland management (Twidwell et al., 2013).

Rangeland managers must minimize tradeoffs between conservation and agriculture production to achieve optimal sustainability (Butsic et al., 2020). However, previous patch-burning research has overlooked the potential benefits to livestock production. With patch-burning we were able to create landscape-level heterogeneity in forage quality and livestock selection. Year to year forage quality and cattle selection variability was higher in patch-burning than continuous, indicating that we were able to create contrast between different patches. The pasture level spatial and temporal patterns of forage quality and grazer selection results in a shifting mosaic of vegetation structure, which has benefits to wildlife diversity and species conservation (Allred et al., 2011; Fuhlendorf et al., 2009).

Conclusions

Livestock producer livelihood relies on monetary returns from grazing livestock and therefore evaluation of the sustainability of grazing management practices should consider both environmental and production impacts. Our results demonstrate that patch-burn grazing provides livestock with patches of high nutritive value forage, which has benefits for livestock production systems. Recently burned patches in the patch-burning had more forage that met the crude protein and net energy for maintenance requirements for grazing cattle in the grazing season. Cattle consistently gained weight under patch-burn management, while cattle did not consistently gain weight in the pastures managed without fire, providing further evidence that patch-burning best meets livestock requirements. This has the potential to reduce grazing season costs for producers, since supplementation is less likely to be required to meet livestock nutrient requirements.

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CHAPTER 2: PRESCRIBED FIRE INCREASES NATIVE GRASSLAND FORAGE MINERAL CONTENT

Abstract

Patch-burn grazing is a livestock management practice that provides a wide range of benefits to ecosystem conservation and livestock production. Mineral nutrition is important for livestock health and performance, but the impact of prescribed fire on mineral concentration of forages in the northern Great Plains remains unknown. In this study, we determined how burning affects the mineral concentration of available forage through the growing season. Data were collected on mixed-grass rangeland at the Central Grasslands Research Extension Center in south-central North Dakota from 2017-2020. Vegetation was clipped from recently burned, one year since fire, two years since fire, and unburned patches on thin loamy ecological sites at the same sampling points in spring and late summer. All samples were analyzed for calcium, phosphorus, magnesium, potassium, copper, iron, manganese, and zinc concentration on a dry weight basis. Burning increased forage mineral concentration across most minerals. Phosphorous, potassium, copper and zinc were higher in burned areas in late spring and summer, while calcium, magnesium and manganese were only higher during the late summer. Iron was increased in longer time since fire patches during the late season sampling. Increased mineral concentration in forage on burned areas has the potential to reduce mineral supplementation costs and improve cow performance through enhanced immune function and reproduction.

Introduction

Grasslands worldwide have evolved under the interaction of fire and grazing disturbances, creating a heterogeneous landscape with a wide range of vegetation structure

(Archibald et al., 2005; Fuhlendorf et al., 2017). These interactions can be mimicked through a grazing management practice called patch-burn grazing (Fuhlendorf & Engle, 2004). Patch-burning concentrates grazer activity in recently-burned patches within large rangeland pastures, creating spatial heterogeneity that enhances ecosystem functioning and biodiversity (Fuhlendorf et al., 2017; Sensenig et al., 2010). Patch-burning also enhances livestock production. Recently burned forage is high in crude protein and low in acid detergent fiber and neutral detergent fiber (Dufek et al., 2014; Scasta et al., 2016), maintains or increases cattle weight gains (Scasta et al., 2016), and buffers livestock production during drought (Allred et al., 2014; Spiess et al., 2020).

Mineral nutrition is an important consideration to maximize cattle production and maintain ranch sustainability through influence on reproduction, health, and growth (Greene, 2000; Suttle, 2010). Essential minerals for cattle include the macro-minerals calcium, magnesium, phosphorus, potassium, sodium, chlorine, and sulfur, and the trace or micro-minerals chromium, cobalt, copper, iodine, iron, manganese, molybdenum, nickel, selenium, and zinc (NASEM, 2016). However, native grassland forage is not always able to satisfy the mineral requirements of grazing cattle throughout the grazing season, decreasing forage utilization and performance (Arthington & Ranches, 2021; McDowell, 1996). In particular, phosphorous, magnesium, copper, zinc, manganese, cobalt, selenium, and iodine are most commonly found to be deficient for cattle in forage (Arthington & Ranches, 2021; Greene, 2000; Suttle, 2010). Free-choice mineral supplementation can be used to meet grazing livestock requirements, but this adds producer costs and individual animal intake can be variable (Greene, 2000). To our knowledge, there are no published examples of grazing management practices shown to increase forage mineral content.

Mineral concentration of forage can vary spatially and temporally because plant communities and soils can be extremely variable on native grasslands. Typically, mineral concentration is greater in legumes and forbs than in grasses, with species-level differences within plant families (Ganskopp & Bohnert, 2003; Grings et al., 1996; Suttle, 2010). Forage mineral concentrations are generally a reflection of the amount of absorbable minerals in the soil (Suttle, 2010). Furthermore, soil pH can influence plant mineral uptake with pH values above six increasing molybdenum, and decreasing manganese and cobalt uptake (Suttle, 2010). Over the grazing season, forage mineral content usually decreases with maturation for phosphorus, potassium, zinc, copper, manganese, and iron since plant maturity causes dilution and translocation of minerals to roots (McDowell, 1996; Suttle, 2010). However, calcium and magnesium content usually increase with grazing season progression and maturation due to accumulation and decreased dilution in the plant (Ganskopp & Bohnert, 2003; Metson and Saunders, 1978).

Limited studies have examined fire effects on forage mineral content, and contradicting results have been observed in the studies that have been published (Anderson et al., 2007; Eby et al., 2014; Umoh et al., 1982; Van de Vijver et al., 1999; Vermeire et al., 2020). The majority of these studies have found some minerals to increase in recently burned forage; however, there is a lack of consistency as to which minerals are impacted by fire (Anderson et al., 2007; Eby et al., 2014; Van de Vijver et al., 1999; Vermeire et al., 2020). Much of this variability can likely be due to different soil mineral content, prescribed fire timing, and plant communities. The short duration of forage mineral increase is the one aspect consistent between studies, with forage mineral content returning to unburned levels by a few months post-fire (Eby et al., 2014; Van de Vijver et al., 1999; Vermeire et al., 2020).

We determine if prescribed fire impacts forage minerals important for beef cattle nutrition. The lack of consistent outcomes in the limited studies examining forage minerals under prescribed fire complicates efforts to ensure proper mineral nutrition of grazing livestock. The objective of this research was to: 1) determine if prescribed fire increases mineral content of forage in rangeland pastures; and 2) ascertain if forage after prescribed fire will better meet recommendations for beef cattle. We hypothesized that post-fire regrowth in patches following spring fire would have greater mineral content than forage in unburned patches, and that this increase would be short-term, lasting the first three months of the grazing season. We also expect that forage in recently burned patches will be closer to meeting the requirements of grazing beef cows.

Methods

Study Location

We conducted this study at the North Dakota State University Central Grasslands Research Extension Center (CGREC) in Stutsman and Kidder counties near Streeter in south-central North Dakota, USA (46°45’N, 99°28’W). Climate at CGREC is characterized as temperate. The Center receives an average growing season precipitation of 361mm with growing season temperature ranging from 12 °C to 21 °C (National Weather Service, 2021).

Pasture vegetation is characterized as mixed-grass prairie and herbaceous cover is primarily Kentucky bluegrass (*Poa pratensis* L.), smooth brome (*Bromus inermis* L.), western wheatgrass (*Pascopyron smithii* [Rydb] À. Löve), and little bluestem (*Schizachyrium scoparium* [Michx] Nash; Spiess et al., 2020).

Study Design

The experimental design and animal management were approved by the North Dakota State University Institutional Animal Care and Use Committee (IACUC A20033). We conducted this study on three pastures managed with patch-burn grazing. Commercial crossbred Angus cow-calf pairs (*Bos taurus*) grazed three 65 ha patch-burn pastures from mid-May to mid/late-October at a stocking rate of 0.5-0.6 ha Animal Unit Months-1. These pastures underwent a spring burning treatment (April) where a quarter (~16 ha) of the pasture was burned each spring, creating a four-year fire return interval. Forage sampling occurred from 2017-2020 during late spring (May) and late summer (September), which corresponded to when cattle started the grazing season and within a month of the end of the grazing season. Patches classified as recently burned received a fire treatment in the sampling year. To minimize variability in mineral content due to different soil types, we only selected clipping points from thin-loamy ecological sites (Sedivec and Printz, 2021). We clipped forage samples from unburned, recently burned, one year since fire, and two years since fire patches. Sampling points remained the same for the duration of the study and followed through the time since fire gradient as assigned.

Forage Collection and Analysis

We clipped plant material 3 cm above the soil surface from a 25 x 25 cm frame to minimize contamination from soil and litter, but still include the live and standing dead material. This forage clipping method simulated feeding station forage removal by grazers. After clipping, we dried samples for 48 hours at a temperature of 60°C in a forced air oven, then ground samples with a Willey Mill (Model 4, Thomas Scientific, Swedesboro, New Jersey) using a 1-mm screen, and finally stored in bags for chemical analysis. We analyzed samples for calcium (Ca), phosphorous (P), magnesium (Mg), potassium (K), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) using atomic absorption spectrophotometry (AOAC, 2010). We then compared our forage mineral content in pastures to recommended levels of forage mineral concentrations. Forage mineral content recommendations were based on the average animal grazing the study pastures: an April calving, 572 kg cow with 8 kg/day peak milk production and 40 kg calf birth weight (NASEM, 2016).

Statistical Analysis

All data were analyzed in the R statistical environment (R Core Team, 2019). We compared mineral concentration between seasons and across a time since fire gradient using linear mixed-effect models using the 'lmer' function from the *lme4* package (Bates et al., 2015). To account for repeated sampling measures and site differences we included pasture and year as crossed random effects. We developed model sets, which included a null model, time since fire only, season only, and time since fire with season as an additive and as an interaction. We then ranked candidate models using Akaike information criterion (AIC). We considered models with ΔAICc $\leq$2 to have the same explanatory power (Burnham & Anderson, 2004). To get pairwise comparisons between time since fire, season or time since fire and season we used 'emmeans' function from the *emmeans* package.

To determine dissimilarity between treatments, we used principal component analysis (PCA) in the *vegan* package (Oksanen et al., 2016) on scaled data. We then conducted post-hoc pairwise comparisons using *vegan*'s envfit (permutations = 99) to determine if there were differences between treatments, years, and sampling periods. We incorporated pasture and year as a random effect (strata) within "envfit" to account for repeated sampling and pasture differences. Pairwise comparisons of multivariate analysis were done using *pairwise.factorfit* from the 'RVAideMemoire' (permutations = 199), with variability from pasture and year accounted for as a random effect (Hervé, 2018). We considered results to be significant for all analysis at $\alpha \leq 0.05$.

Results

There was a difference between burned and unburned patches in early and/or late sampling for almost all minerals tested (Figure 2.1). The model with the interaction between time since fire and season had the best fit in all minerals except phosphorous, which had the best fit with the additive time since fire and season model. Calcium was not different ($p>0.05$) between any patches early in the grazing season. At late grazing season, calcium was greater in the burned patches than all other patches (burned vs. 1 year since fire: $t=4.083$, $p< 0.001$; burned vs. 2 year since fire: $t= 5.026$, $p<0.001$; burned vs. unburned: $t=6.984$, $p<0.001$). Phosphorous content was greater in recently burned patches than all other patches during early and late grazing season sampling (burned vs. 1 year since fire: $t=3.7$, $p= 0.001$; burned vs. 2 year since fire: $t=4.461$, $p<0.001$; burned vs. unburned: $t=8.586$, $p<0.001$). During early grazing season, potassium was greater in recently burned than all other patches (burned vs. 1 year since fire: $t=2.755$, $p= 0.031$; burned vs. 2 year since fire: $t=4.806$, $p<0.001$; burned vs. unburned: $t=10.076$, $p<0.001$), and one and two years since fire patches than unburned (1 year since fire vs. unburned: $t=6.372$, $p< 0.001$; 2 year since fire vs. unburned: $t=3.118$, $p<0.011$). But by late grazing season sampling, potassium was only greater in burned patches than all other patches (burned vs. 1 year since fire: $t=4.603$, $p< 0.001$; burned vs. 2 year since fire: $t=3.729$, $p=0.001$; burned vs. unburned: $t=7.278$, $p<0.001$). Magnesium was not different between any time since fire patches early in the grazing season. However, similar to calcium, magnesium content was greater in the recently burned patch than all other patches by late grazing season sampling (burned vs. 1 year since fire: $t=4.78$, $p<0.001$; burned vs. 2 year since fire: $t=4.942$, $p<0.001$; burned vs. unburned: $t=7.196$, $p<0.001$).

During early grazing, copper content was not different between recently burned and one year since fire patches (burned vs. 1 year since fire: $t=1.998$, $p=0.191$); however, both were greater than longer time since fire patches (burned vs. 2 year since fire: $t=5.8$, $p=<0.001$; 1 year since fire vs. 2 year since fire: $t=3.928$, $p<0.001$; burned vs. unburned: $t=5.676$, $p<0.001$; 1 year since fire vs. unburned: $t=3.119$, $p=0.011$). However, by the late grazing season, forage copper was only greater in recently burned and two year since fire patches than unburned patches (burned vs. unburned: $t=5.083$, $p< 0.0001$; 2 year since fire vs. unburned: $t= 3.023$, $p<0.014$). Manganese content was not different between the varying time since fire patches early in the grazing season, but late in the grazing season was greater in burned and one year since fire patches than the unburned (burned vs. unburned: $t=2.716$, $p= 0.035$; 1 year since fire vs. unburned: $t=3.663$, $p=0.002$). Early in the grazing season, zinc was greater in recently burned patches than unburned patches (burned vs. unburned: $t=3.428$, $p=0.004$). However, late in the grazing season recently burned patches were greater than all other patches (burned vs. 1 year since fire: $t=5.225$, $p< 0.001$; burned vs. 2 year since fire: $t=5.172$, $p<0.001$; burned vs. unburned: $t=8.900$, $p<0.001$). Iron forage content patterns are less clear than the other minerals, and only the 2 year since fire patches were greater than unburned patches late in the grazing season (2 year since fire vs. unburned: $t=3.42$, $p<0.004$).

In general, forage in the recently burned patch best met the recommended mineral intake levels of a lactating beef cow based on NASEM (2016; Figure 2.1). No patches met copper recommended forage levels at any sampling period or magnesium during early grazing season sampling, but the recently burned patch was the closest to meeting copper recommendations. All other instances where the mineral content in recently burned patch was not greater than other patches, it was still above recommendations.

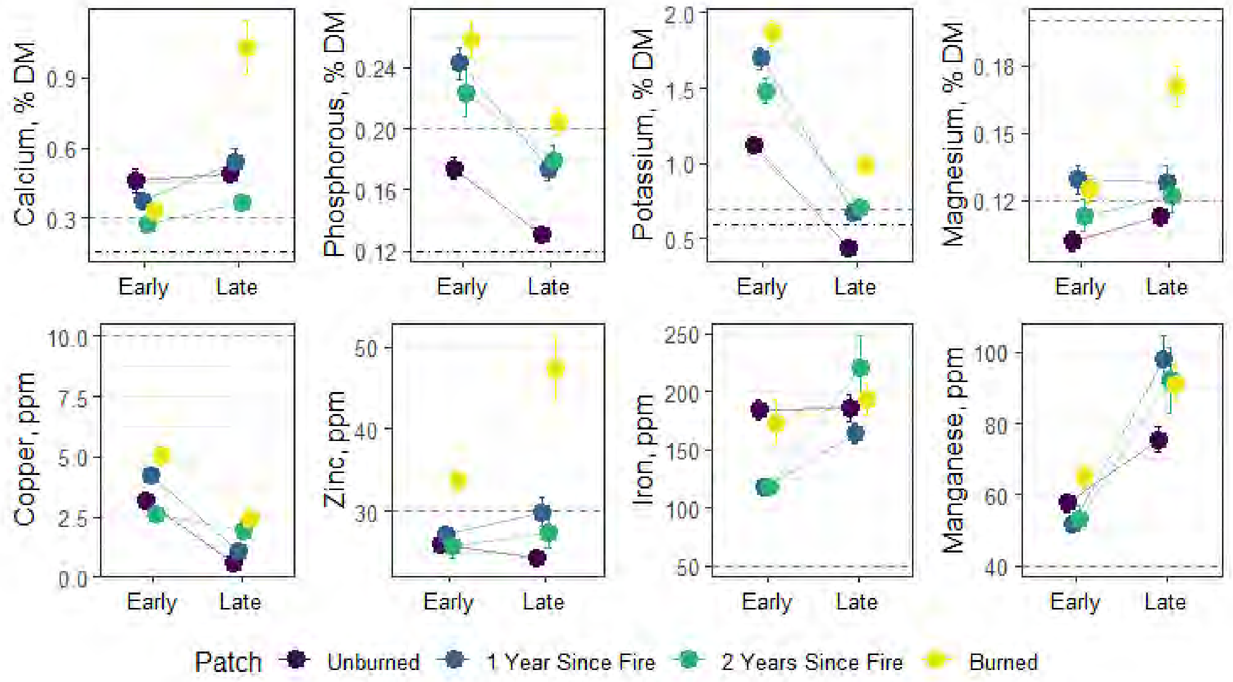

Figure 2.1. Mean and standard error of calcium, phosphorous, potassium, magnesium, copper, zinc, iron and manganese content in forage by sampling season. Time since fire patches include recently burned, 1 year since fire, two year since fire and unburned patches at CGREC from 2017-2020. Calcium, phosphorous magnesium and zinc are expressed as percent dry matter (% DM). Copper, iron, manganese and zinc are expressed as parts per million (ppm). The grey dashed lines in calcium, phosphorous, potassium and magnesium represent lactating beef cow recommended forage levels at the beginning of the grazing season, and black dash dot lines represent late season beef cow recommendations (NASEM, 2016). Dashed lines in copper, zinc, iron and manganese represent general season long beef cow recommended forage levels (NASEM, 2016).

The PCA showed clusters of different time since fire groups with calcium, zinc, magnesium, manganese, copper, phosphorous, and potassium more strongly associated with burned patches than unburned patches (Figure 2.2). The first three axes explained 70% of the variation seen in the PCA. Values along PCA Axis 1 (32 % of variation) and PCA Axis 2 (24% of variation) fairly equally associated with all minerals. However, iron was not associated with PCA Axis 1 and is likely responsible for much of the variability. Time since fire (r^2= 0.13, p= 0.005) and season (r^2= 0.25, p=0.005) had significant correlation and explained variability within the PCA. While year (r^2= 0.05, p=0.005) was a significant term, it poorly fit the variation in the

PCA. Based on pairwise factor fitting of the PCA, one and two years since fire patches were not different (p=0.13), while all other patches were different from each other (p=0.012). Pairwise comparisons also indicated that 2017 was significantly different than all other years of sampling (p=0.02), which were not different from each other.

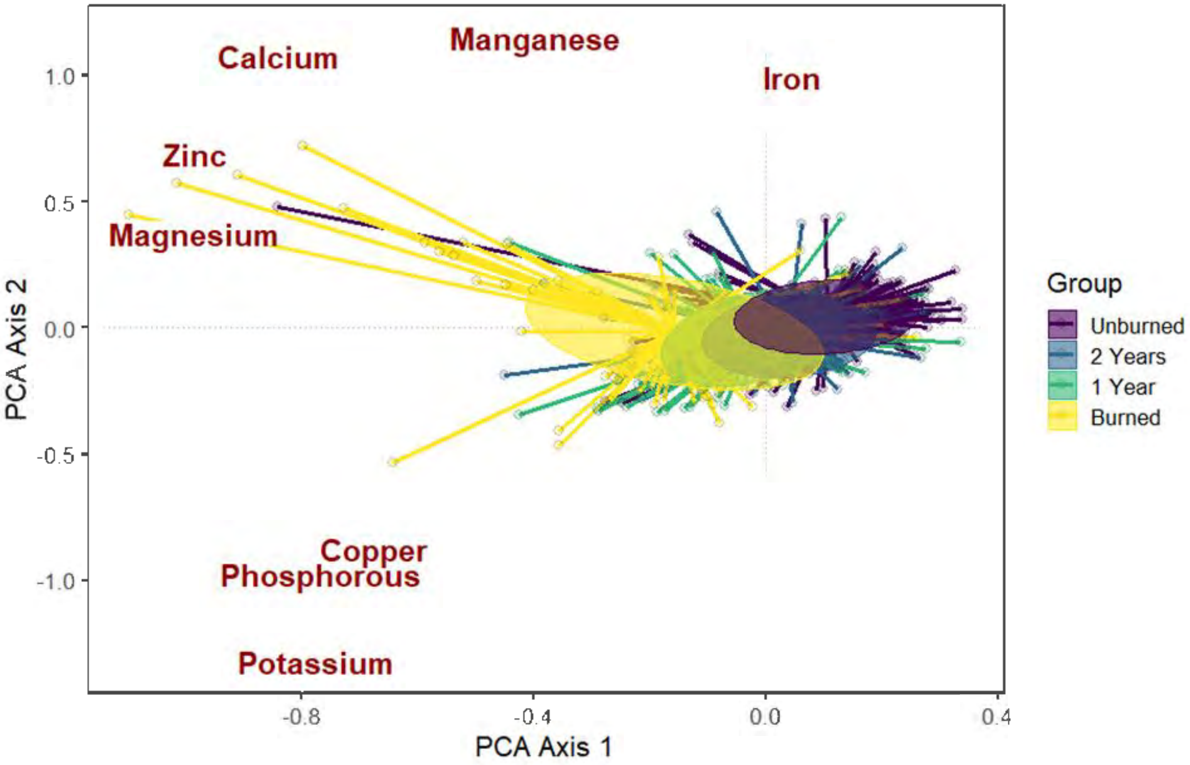

Figure 2.2. Principal components analysis (PCA) scatterplot based on minerals concentration of forage with varying time since fire in patch-burn grazing pastures. Groups represent recently burned, one year since fire, two years since fire, and unburned patches.

Discussion

We determined if patch-burn grazing increases forage mineral concentrations after fire for eight minerals important for nutrition of beef cattle. Our results indicate patch-burn, generally increased forage mineral concentration in recently burned patches for the extent of the grazing season. Most of the minerals tested exceeded forage mineral concentration recommendations throughout the grazing season on recently burned patches.

Increased forage mineral concentrations, which differ from previous study results, are likely due to the combined interaction of fire and grazing implemented in patch-burning rather than fire alone. While most studies have found some minerals to increase with fire, the specific minerals are inconsistent from study to study. For example, no increases in forage calcium concentrations with fire were found in some studies (Eby et al., 2014; Vermeire et al., 2020), while another found calcium increased, which lasted last longer than any other minerals (Van de Vijver et al., 1999). A three month increase in forage mineral concentration following fire, has been found in a few studies (Eby et al., 2014; Van de Vijver et al., 1999). However, by five months since fire, all minerals except iron were greater in the recently burned patch in our study. Furthermore, copper, potassium, and manganese remained higher in one year since fire patches than unburned patches early in the grazing season, indicating that patch-burning sustains some mineral increases past the first year of fire. Mineral increases have been attributed to reduced age of plant tissue, increased leaf to stem ratio, and nutrients distributed over less biomass in post-fire vegetation (Van de Vijver et al., 1999). Therefore, differences in the duration of mineral increase between our study and previous research are likely due to continued attraction and grazing of the recent burn patch, delaying or eliminating plant maturity.

Seasonal forage mineral trends are not overridden by patch-burn grazing. Similar results have been found in rotational grazing studies where seasonal mineral fluctuations persisted even though forage remained in an immature state (Kappel et al., 1985). Seasonal patterns of forage minerals with fire have not been well established in previous research, but are apparent in all minerals in our study (Anderson et al., 2007; Eby et al., 2014; Van de Vijver et al., 1999; Vermeire et al., 2020). Factors known to influence mineral concentration in rangeland forage managed without fire, such as plant species, soil characteristics, precipitation, and maturity, continue to influence mineral concentration in rangeland managed with fire (Arthington & Ranches, 2021; Suttle, 2010). Although forage mineral concentration in our study was higher in recently burned patches, phosphorous, potassium and copper still decline as expected in forage managed without fire, similar to Metson & Saunders (1978) and Suttle (2010). While zinc is expected to decline as the grazing season advances, we found it only happened in the unburned patch, with patches that received fire increased from early to late grazing season.

Mineral concentration in the recently burned patch was generally adequate to meet recommended levels of calcium, phosphorous, potassium, zinc, iron, and manganese for lactating cows (NASEM, 2016). Calcium, phosphorous, magnesium, and potassium recommendations are dependent upon cow size, physiological state, and milk production (NASEM, 2016), so requirements will vary between individual animals and throughout the grazing season. However meeting the recommended mineral levels does not indicate that requirements are being met (Suttle, 2010). Factors such as the location of the mineral in the plant, chemical form, and mineral interactions all influence bioavailability, or the accessibility, absorbability, retainability, and functionality of minerals, therefore impacting the ability for requirements to be met by forage (Suttle, 2010). Furthermore, even if forage mineral content does not meet requirements, it does not necessarily mean animals will be deficient (Arthington & Ranches, 2021). Cattle can often withstand short periods of dietary mineral inadequacy because bones, blood, and liver provide a substantial pool of minerals to draw from when needed (Arthington & Ranches, 2021; Spears & Weiss, 2014).

Mineral ratios are an important consideration when determining cattle mineral requirements since many minerals interact with each other. Calcium to phosphorous ratios between 1:1 to 1:7 are considered to result in similar cattle performance (NASEM, 2016). Early grazing and late summer calcium to phosphorous ratios were within the recommendations at 1.2:1 and 5:1 in our study. Ratios of potassium to calcium plus magnesium are important to consider in early grazing season for the prevention of grass tetany, with incidence of disease increasing linearly above 2.2:1 ratio (Kemp & t' Hart, 1957; Suttle, 2010). In our recently burned patch, the tetany ratio is 4:1, potentially increasing the likelihood of grass tetany occurrence in cows. As a result, mineral supplementation to cattle grazing patch-burn pastures may still be required to adequately meet requirements and prevent mineral related disease.

Copper was deficient based on recommended levels (NASEM, 2016) across all treatments, and the higher concentration in the burn patch might not be substantial when antagonistic interaction with molybdenum, sulfur, and zinc are considered (Suttle, 2010). Zinc concentrations were high in the recently burned patch, especially late in the grazing season, and since both minerals use the same absorption sites in the animal, copper absorption is likely to be impaired (Suttle, 2010). Other studies have also found increases in sulfur with prescribed fire compared to control plots, which further indicates bioavailability of copper is likely decreased with patch-burning (Vermeire et al., 2020). Drinking water can also be a source of high sulfur content, reducing copper concentration in beef cattle (Penner et al., 2020; Smart et al., 1986). While we did not measure molybdenum content of forage, a previous study at the same location found forage molybdenum in continuous grazing pastures to be below maximum recommended intake levels (McCarthy et al., 2021). No previous fire studies have examined fire impact on molybdenum, but levels reported at the study site without prescribed fire would be high enough to impair copper absorption due to low copper levels (Paterson & Engle, 2005).

Lower amounts of fibrous forage components in the recently burned patch may further provide benefits for mineral absorption in livestock. Recently burned patches are lower in ADF, which includes lignin and cellulose, than other patches (Dufek et al., 2014; Gullap et al., 2018). Lignin and cellulose often form clusters, bound by minerals, which reduces the absorbability of these minerals (Moreira et al., 2013). Therefore, lower amounts of ADF could result in higher absorption of forage minerals.

Precipitation largely drives mineral concentration patterns and differences between mineral concentrations in 2017 and all other years can likely be attributed to a drought during the grazing season (Lalman & McMurphy, 2009; Spiess et al., 2020; Suttle, 2010). Drought has been shown to increase mineral forage mineral concentration for most minerals, while above average precipitation years tend to decrease forage mineral concentrations (Ganskopp & Bohnert, 2003; Grings et al., 1996). In 2019, the study area had above average growing season precipitation but, did not appear to affect forage mineral concentrations from average precipitation years. All previous studies have evaluated mineral content for one or two growing seasons. Some of the mineral content variability seen with previous studies is likely due to variable precipitation patterns, and timing of fire in relation to wet or dry seasons over short study durations (Eby et al., 2014; Van de Vijver et al., 1999; Vermeire et al., 2020).

Soil pH can directly influence mineral uptake by plants (Suttle, 2010) and might be limiting plant uptake in our study. While we did not directly measure soil pH, a study conducted on the same 2017 to 2018 prescribed fires we sampled and found soil pH to range from 6.15 to 7.2 after fire (Gerhard et al., 2022). At these pH levels, manganese and zinc concentrations have been found to be decreased compared to lower pH levels in other studies (Suttle, 2010). However, forage manganese and zinc content increased in the recently burned patch in our study. Since no pre-burn soil pH was reported by Gerhard et al. (2022), this could indicate that either pH was not affected by fire, or that fire effects on plant morphology and phenology may override negative effects of increased soil pH. Another study examined soil pH as a mechanism for changes in plant mineral concentration after prescribed fire and found no change in pH; therefore, changes were attributed to plant morphological changes (Van de Vijver et al., 1999).

This study provides a basis for understanding forage mineral concentrations when grazing patch-burned pastures, however, gaps are apparent in current literature. While prescribed fire increased forage mineral content, further research is needed to determine if these differences are also apparent in cattle mineral stores through the grazing season. Differences between patch-burning and other grazing strategies should also be explored to further determine how grazing management impacts forage mineral concentrations. Because of potential trace mineral antagonistic effects between Cu, sulfur, molybdenum, future research should include these minerals in analysis to provide a better understanding of how patch-burning alters mineral concentration requirements. Vitamin and mineral supplementation of cattle often coincide, but to our knowledge, there are no published studies examining the effects of forage vitamin content with prescribed fire, which could be another potential avenue for future studies.

Conclusions

Our study suggests that, in general, prescribed fire can increase mineral concentration of forage. Furthermore, in patch-burn grazing where at least one patch is burned each year, an area is created with forage regrowth following fire each grazing season. Patch-burn grazing could also potentially sustain mineral concentrations for longer periods than prescribed fire alone due to delaying forage maturity. While mineral concentrations varied between the beginning and end of grazing sampling, the recently burned patch was above recommendations except for copper and early season magnesium. Supplementation may still be necessary in patch-burn grazing to ensure adequate copper and prevent grass tetany in the early grazing season due to low magnesium concentrations. Increased forage mineral concentration in recently burned areas has the potential to reduce producer mineral supplementation costs and increase cow performance, which is a benefit of patch-burning to livestock production. Understanding forage mineral trends provides producers with insight into custom supplemental mineral formulations or strategies to maximize cattle performance and profitability.

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CHAPTER 3: PATCH-BURNING BENEFITS LIVESTOCK PERFORMANCE OVER OTHER CONSERVATION-BASED MANAGEMENT STRATEGIES

Abstract

Livestock performance has a direct impact on profitability of livestock production operations, making it an important consideration when evaluating the sustainability of grazing management practices. But few studies have compared cow and calf gains between conventional grazing management, rotational grazing that creates heterogeneity and conservation-based management like patch-burn grazing. We compared cow and calf weight gain on patch-burn, continuous, and rotational grazing. Data were collected on experimental rangeland pastures at Central Grasslands Research Extension Center in south-central North Dakota in 2018, 2019 and 2020. We grouped cows into pastures in May based on age and weight. Cows in their first to third parity (calf number) were grouped in young age class pastures, and all other cows were grouped in mature age class pastures. All replicates of each grazing strategy received an equal balance of young and mature age class cows. We weighed cows on two consecutive days and calves one day before turnout. We used these weights to sort animals to maintain a consistent stocking rate and average cow weight across pastures. Two-day weights were collected for both cows and calves when removed from pastures. Average daily gain (ADG) was calculated by subtracting the average turnout weight from the average final weight, then dividing by the number of days grazed. Age class affected calf ADG, but not cow ADG. Cow and calf ADG were lower in the rotational system compared to patch-burn and continuous grazing. Similar ADG was observed between patch-burn and continuous grazing for cows and calves across mature and young age classes. However, patch burning had the least annual variability in cow

ADG. These data suggest that producers can use patch-burning as a management practice to achieve ecosystem management goals without sacrificing livestock performance.

Introduction

Rangelands worldwide often simultaneously support delivery of multiple ecosystem services, including provisioning services that support commercial livestock production, as well as regulating and supporting services that are critical to ecological processes (Millennium Ecosystem Assessment, 2005). Therefore, sustainable grazing management practices must balance environmental protection and livestock production to maintain ecosystem functionality and economic viability of grazing rangelands (MacLeod and McIvor, 2006).

The goals of conservation and production land-uses can conflict. For example, continuous grazing and most rotational grazing systems support a narrow suite of biological niches since they promote even forage utilization by homogenizing grazer distribution over time and space, decreasing grazer selectivity (Briske et al., 2008; Holechek et al., 2010). Conversely, many conservation-based grazing management strategies are viewed to limit livestock production, often necessitating reduced stocking rates or deferring grazing to periods of sub-optimal forage nutritive value (MacLeod and McIvor, 2006; O'Connor et al., 2010).

Patch-burn grazing is a heterogeneity-based management strategy that supports conservation, but might also directly support livestock production. Patch-burn grazing aims to mimic pre-European fire and grazing disturbance patterns (Fuhlendorf and Engle, 2004). The fire-grazing interaction created a shifting mosaic of vegetation patches varying in structure across the landscape, which supported a broad range of biodiversity (Fuhlendorf et al., 2017). Patch-burning combines spatially-patchy prescribed fire and livestock grazing to create similar vegetation structural patterns (Fuhlendorf and Engle, 2004). Grazers are attracted to the high nutritive value forage produced after prescribed fire, creating contrast between patches with a longer time since fire (Leonard et al., 2010; Wallace and Crosthwaite, 2005). While high nutritive value forage drives the fire-grazing interaction in creating heterogeneity, it also benefits livestock production. During periods of drought, patch-burning stabilizes forage availability, producing a ‘grass bank’ that mitigates the negative effects of reduced precipitation on livestock performance (Allred et al., 2014; McGranahan et al., 2014; Spiess et al., 2020). Furthermore, there are potential benefits to livestock nutrition through increased minerals, increased crude protein, and reduced fiber concentrations in forage regrowth after fire (Allred et al., 2011; Raynor et al., 2015; Sensenig et al., 2010; Wanchuk et al., 2021).

While many different rotational grazing systems exist, traditionally these systems were developed to prevent overgrazing by allowing for adequate plant recovery and evenly distributing grazers across pastures with fencing (Holechek et al., 2010). Stocking rates, grazing density, number of paddocks, and grazing periods can vary greatly between different grazing systems (Teague et al., 2013). For example, rotational systems can range from light stocking with two or three paddocks, to 30+ paddocks stocked up to 200% over recommended stocking rates and grazed for short durations (Teague et al., 2008). With concern for conservation, rotational grazing has been proposed as a potential management strategy to create structural heterogeneity among paddocks (Cid et al., 2008; Milligan et al., 2020), but has not been evaluated for livestock performance. While it has been suggested that rotational grazing enhances livestock performance by ensuring adequate plant recovery and modifying livestock distribution, grazing intensity, and feeding behavior (Teague et al., 2013), literature reviews have found that generally, rotational grazing systems do not increase livestock performance compared to continuous grazing (Briske et al., 2008; Hawkins, 2017).

Multiple measures of livestock performance exist, but weight gains are a commonly used metric of livestock performance that directly impact producer monetary gains. Livestock weight gain is regulated by forage quantity and forage nutritive value (Sollenberger and Vanzant, 2011). During periods of limited forage quantity, weight gains increase linearly with increasing forage quantity (Rouquette, 2016; Sollenberger and Vanzant, 2011). Eventually, the effects of increasing quantity plateau and forage nutritive value will define the upper limits of livestock weight gains (Kearney et al., 2022; Rouquette, 2016; Sollenberger and Vanzant, 2011). Forage nutritive value and quantity are heavily influenced by stocking rate, which provides the greatest impact on livestock weight responses (Rouquette, 2016; Sollenberger and Vanzant, 2011).

While previous research has evaluated patch-burn in comparison to continuous grazing on livestock weight gains (Limb et al., 2011; Spiess et al., 2020), there have been no comparisons between patch-burn and rotational grazing. Furthermore, livestock performance in heterogeneity-based conservation rotational grazing systems has not been evaluated. Limited studies have evaluated the effects of patch-burning on cow-calf performance (Limb et al., 2011; Spiess et al., 2020). Previous research has established that livestock weight gains are not hindered by patch-burning in comparison to continuous grazing or a single-homogenous yearly fire (Farney et al., 2017; Limb et al., 2011; Scasta et al., 2016).

We evaluated livestock performance on pastures managed for heterogeneity through two different methods compared to a conventional grazing management practice. Specifically, we evaluate if patch-burning will produce greater cow and calf weight gains with less annual variability than a conservation-based rotational grazing system and continuous grazing. We hypothesize that patch-burning will result in increased weight gains for cows and calves than rotational and continuous grazing. Additionally, we expect patch-burning to result in less annual variability in weight gains.

Methods

Study Location

We conducted this study at the North Dakota State University Central Grasslands Research Extension Center (CGREC) in Stutsman and Kidder counties near Streeter in south-central North Dakota, USA (46°45’N, 99°28’W). Climate at CGREC is characterized as temperate. The Center receives an average growing season precipitation and normal mean annual precipitation of 361mm and 504mm; respectively, with growing season temperature ranging from 12 °C to 21 °C (National Weather Service, 2021).

This area is northern-mixed grass prairie comprised of introduced perennial cool-season grasses, native perennial warm and cool-season grasses, forbs, legumes, and shrubs. Common plant species include Kentucky bluegrass (*Poa pratensis* L.), smooth brome (*Bromus inermis* L.), western wheatgrass (*Pascopyron smithii* [Rydb] À. Löve), green needlegrass (*Nassella viridula* [Trin.] Barkworth), blue grama (*Bouteloua gracilis* [Willd. ex Kunth] Lag. ex Griffiths), little bluestem (*Schizachyrium scoparium* [Michx] Nash), goldenrods (*Solidago* spp.), silverleaf scurfpea (*Pediomelum argophyllum* [Pursh] J. Grimes), and leadplant (*Amorpha canescens* Pursh)(Limb et al., 2018). The most common woody species in western snowberry (*Symphoricarpos occidentalis* [L.] S. F. Blake).

Study Design

We conducted this study during the 2018-2020 grazing seasons. The grazing season occurred between mid-May to mid/late-October. Pastures were grazed with crossbred Angus cows (*Bos taurus*) that calved from the end of March to the beginning of May. Calves were offspring of multiple Angus sires, with most sires kept the same between years. Each year we synchronized females in late June using a 7-CoSynch artificial insemination protocol and bred to several different sires. We turned out natural service cleanup bulls on pasture shortly after artificial insemination and cows were exposed for approximately 45 days.

We included twelve pastures (~65 ha) in the study, with four replicates of three grazing strategies: patch-burn grazing, continuous grazing, and conservation-based rotational grazing. The patch-burn grazing began in 2017, with one quarter (~16 ac) of the pasture undergoing a spatially discrete prescribed fire each spring to create a four-year burn cycle. Cattle were allowed unrestricted access to all patches during the grazing season, similar to continuous grazing.

The rotational grazing system was designed as a modified twice over rest-rotational grazing system and implemented in 2018. This rotational system was a hybrid system of the twice-over rotation (Biondini and Manske, 1996; Sedivec and Barker, 1991) and rest rotation grazing system (Hormay and Talbot, 1961) used throughout the northern Great Plains. For this study, we modified the system to target similar structural heterogeneity between grazing paddocks as created with patch-burning system patches. Each 65-ha pasture was cross-fenced to create four paddocks with a central water source. At the beginning of the study, each paddock was assigned to one of four target grazing intensities: heavy use (>60% biomass disappearance), full use (40% to 60% disappearance), moderate use (20% to 40% disappearance) and rested (no grazing in the grazing season). Cattle rotated twice within the pastures throughout the grazing season (35% of the grazing days in the first rotation, 65% of the grazing days in the second rotation) for approximately 72-, 54- and 27-day days total in each paddock, based on targeted desired use. The grazing intensity of each paddock was also rotated every year resulting in each paddock receiving all of the four grazing intensities over four years. Every year, heavy use pastures transitioned to rested, full use to heavy use, moderate to full use, and rested to moderate.

We maintained the same stocking rate over a four-year period between all grazing strategies at 0.5-0.6 ha AMU-1. However, because one paddock is rested each year in the rotational grazing system to create structural heterogeneity, the within-year stocking rate is approximately 33 percent heavier compared to patch-burn and continuous grazing.

Livestock Weight Collection

In mid-May, cows were split into pastures based on age and weight. Before turnout, we weighed cows on two consecutive days to determine average turnout weight for each cow and weighed calves on one day. Cows in their first to third parity (calf number) were grouped in the young age block and cows in their fourth or more parity in the mature age block. Each grazing strategy had two young and two mature age block pastures each year. We then sorted cows randomly by weight to maintain consistent stocking rates and average cow weight across pastures. Following removal from the pastures in mid/late-October, cows and calves were weighed on two consecutive days to determine an average final weight. We calculated average daily gain (ADG) for cows and calves by subtracting the average turnout weight from the average final weight then dividing by the number of days spent grazing.

Data Analysis

We completed all data analysis using the R statistical environment (R Core Team, 2019). We compared ADG for cows and calves between grazing strategy with linear mixed-effect models using the ‘lmer’ function from the *lme4* package (Bates et al., 2015). To account for repeated sampling measures and pasture differences, we included year and pasture as a nested random effect along with individual cow added as another random effect. We then developed model sets, which included a null model, grazing strategy only, cow age class only, and grazing strategy with age class as an additive and as an interaction. We next ranked candidate models using Akaike information criterion (AIC), considering models with ΔAICc ≤ 2 to have the same explanatory power (Burnham and Anderson, 2004). We used type II ANOVAs to test for grazing strategy and age class significance. Post-hoc analysis was done with ‘glht’ function from the *multcomp* package to determine pairwise comparisons using the Tukey method (Hothorn et al., 2008). For all analyses we considered results to be significant at $\alpha \leq 0.05$.

We determined annual variability of cow and calf weight gains for each grazing strategy. First, we calculated the standard deviation ADG for each grazing strategy each year. We then calculated mean and standard error of the standard deviation for each grazing strategy over study duration.

Results

Cow ADG was different between grazing strategy (χ^2=18.08, p<0.001), but not cow age class (χ^2=0.17, p=0.73, Figure 3.1). Continuous and patch-burn grazing had a higher cow ADG than the rotational grazing system (rotational- continuous: Z=-3.40 p= 0.002; rotational- patch-burn: Z=-3.90, p<0.001). However, continuous and patch-burn grazing were not different from each other (patch-burn vs. continuous: Z= 0.47, p= 0.88).

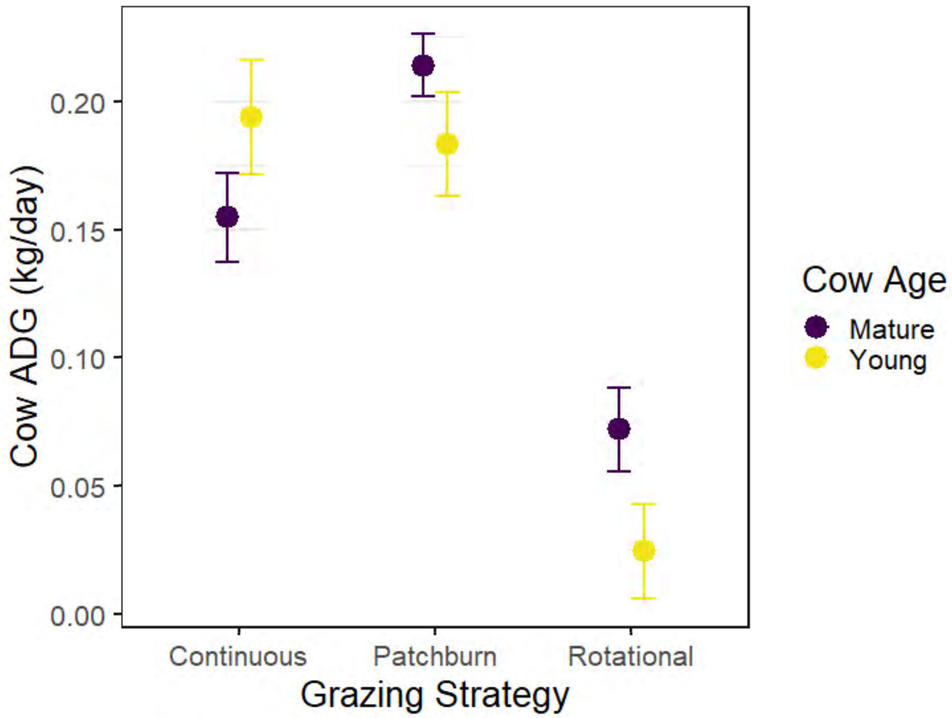

Figure 3.1. Cow average daily gain (ADG, kg/day) mean and standard error for continuous, patch burn and rotational grazing strategies. Mature cow age class is represented in purple and young cow age class is in yellow.

Calf ADG was different between grazing strategies (χ^2= 36.19, p<0.001) and cow age class (χ^2= 63.28, p<0.001, Figure 3.2). Similar to cow weight gains, continuous and patch-burn grazing had higher calf ADG than rotational grazing (rotational- continuous: Z=-4.35 p< 0.001; rotational- patch-burn: Z=-5.76, p<0.001). Continuous and patch burn grazing were not different from each other (patch-burn vs. continuous: Z= 1.37, p= 0.36). Calf ADG was higher in the mature age class cows than young age class cows across all grazing strategies.

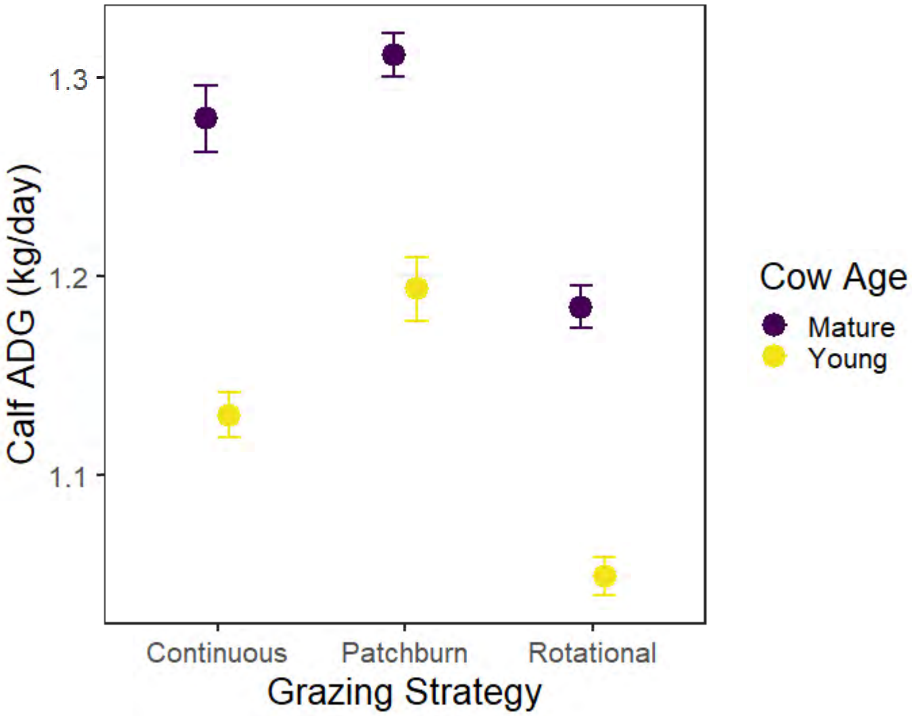

Figure 3.2. Calf average daily gain (ADG, kg/day) mean and standard error for continuous, patch burn and rotational grazing strategies. Mature cow age class is represented in purple and young cow age class is in yellow.

Patch-burn grazing had a lower annual variability in cow weight ADG than rotational and continuous grazing (Figure 3.3). Rotational and continuous grazing had similar amounts of annual variability in cow ADG annual variability. Calf ADG had the lowest annual variability in the rotational grazing system, followed by patch-burning and lastly continuous grazing.

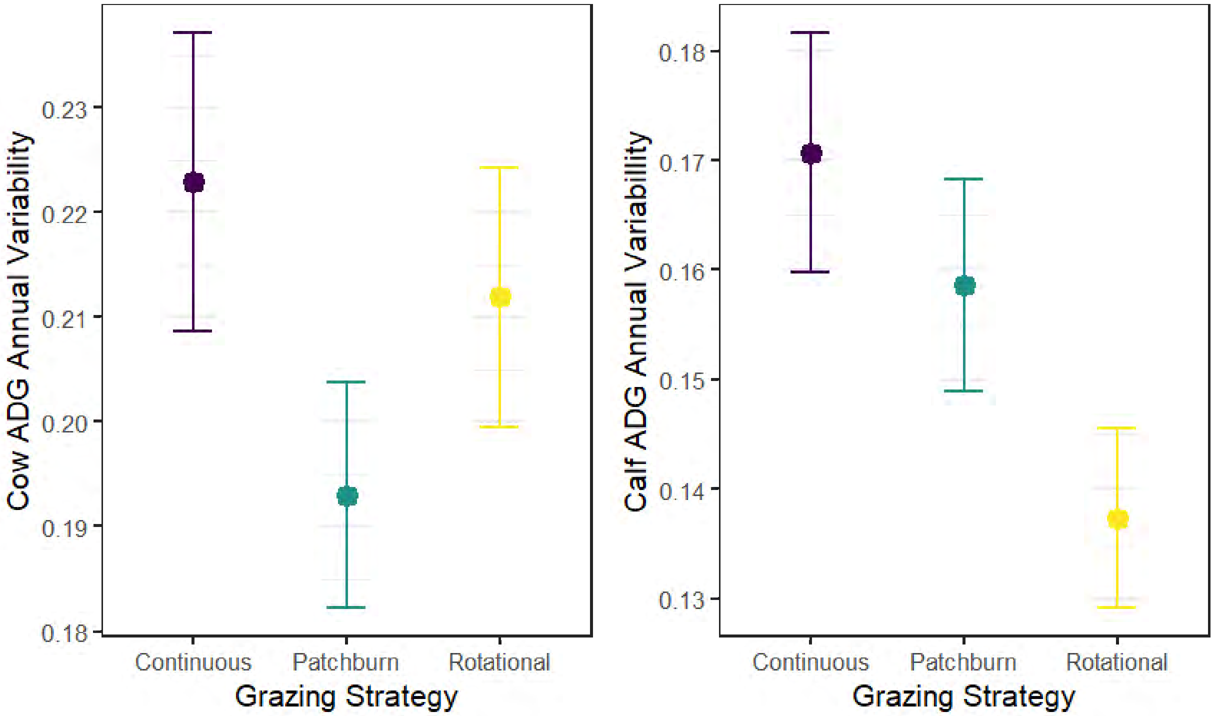

Figure 3.3. Annual variability of average daily gain (ADG) for continuous, patch-burn and rotational grazing. The plot on the left displays cow ADG variability and the plot on the right displays' calf ADG variability.

Discussion

When evaluating grazing management practices, consideration needs to be given to environmental sustainability and livestock production. Benefits of patch-burning for biodiversity and conservation efforts have been established (Fuhlendorf et al., 2009; Hovick et al., 2015), but limited studies have examined livestock performance. We determined that patch-burn grazing can be a suitable conservation-based management strategy to maintain livestock performance. While patch-burn grazing did outperform the rotational grazing system, there were no differences in cow and calf weight gains between patch-burn and continuous grazing. However, cow weight gains had the least annual variability with patch burn grazing.

Similar to our results, studies have found livestock performance in patch-burning did not differ from conventional grazing (Farney et al., 2017; Scasta et al., 2016; Spiess et al., 2020).

Variation in calf weight gains was also less than in continuous grazing (Limb et al., 2011), but the variability of cow weight gains is novel to our study. It is important to note that in the young age class in 2020, continuous grazing pastures produced weight gains that were much higher than any previous years. This was likely because these pastures were stocked with mostly cows in their first parity that were from another trial and these cows gained several hundred pounds on pasture. While our study only followed weight gain in the first burn cycle of patch burn grazing, there is some evidence that cattle on patch-burned pastures might outperform those in conventional continuous grazing after a full burn cycle (Limb et al., 2011).

Forage quantity and nutritive value are evident as drivers of livestock performance in all grazing strategies. Patch-burn grazing produces forage with high nutritive value in the recently burned patch, but with low standing crop available for grazing at a given point in time (Allred et al., 2011; Sensenig et al., 2010; Spiess et al., 2020). However, longer time since fire patches are available to supplement forage mass which prevents livestock performance from declining due to low forage availability (Grant et al., 2019). Heavy and full use grazing intensities keep forage in a relatively immature state, which provides grazers with forage of adequate nutritive value (Sollenberger and Vanzant, 2011). But, forage biomass and allowance are likely limiting individual animal performance in our study, especially in the rotational grazing system (Sollenberger and Vanzant, 2011). High forage quantity availability is associated with greater bite-size, and intake which has also been linked to greater performance; however, intake is also limited by low forage nutritive value (Van Soest, 1994).

Diet selection allows livestock to mitigate spatio-temporal patterns of forage quality that have negative impacts on livestock weight gains. Rangelands are heterogeneous in spatial and temporal factors that influence forage nutritive value, such as plant community, disturbance patterns, soil types, precipitation, and temperature (Fynn, 2012; Ganskopp and Bohnert, 2009; Kearney et al., 2022). This affects forage resources and directly influences seasonal patterns of livestock weight gains (Ganskopp and Bohnert, 2009; Kearney et al., 2022). Weight gains are limited by forage biomass and nutritive value when there is reduced opportunity for selection, and intake (Rouquette, 2016; Sollenberger and Vanzant, 2011). On patch-burn and continuous grazing, cows were able to choose where to graze and select the highest available quality forage throughout the grazing season (Venter et al., 2019). However, most rotational systems are designed to limit selection of high quality forage and encourage even grazing of all species to prevent negative effects of overgrazing the most palatable species (Teague et al., 2013). While patch-burning grazing also seeks to override selectivity, this is at a much finer, feeding station spatial level, and done by homogenizing forage to be high quality in the area where grazing is desired (Raynor et al., 2016).

Stocking rate may have driven differences seen in cattle weight gains in our study. The negative relationship between increased stocking rates and livestock weight gains has been well established because of its influence on forage nutritive value and available forage biomass (Pinchak et al., 1990; Porensky et al., 2016; Thomas et al., 2015). The rotational grazing system in our study was stocked 33% heavier within years compared to our other grazing strategies due to a paddock being rested each year to create conservation habitat. With the increased stocking rate on this grazing system, individual livestock performance suffered, resulting in lower weight gains than patch-burn and continuous grazing. However, a rested paddock was essential to achieve structural heterogeneity goals. Stocking rates, in combination with the high grazing intensity in the heavy use cell, further reduce forage biomass availability and selectivity. Increasing grazing intensity limits forage mass allowance, which also has a significant impact on weight gains (Burns et al., 1989). This likely results in decreased weight gains as cattle grazed the heavy use cell. Even through adaptive management, rotational grazing is unable to mitigate the negative effects of stocking rate on individual livestock performance compared to continuous grazing at the same stocking rate (Augustine et al., 2020). At moderate stocking rates, foraging behavior and re-grazing of individual plants is similar regardless of grazing strategy (Porensky et al., 2021; Venter et al., 2019).

Patch-burning decouples precipitation effects on livestock gains (Allred et al., 2014; Spiess et al., 2020), which explains why cow ADG was less annually variable in patch-burning compared to rotational and continuous grazing. Rainfall and livestock gains are closely coupled since rainfall influences forage nutritive value and biomass, and often accounts for more variability in livestock gains than stocking rate in continuous and rotational grazing (Briske et al., 2008; Fynn, 2012; Fynn and O'Connor, 2000; Hawkins, 2017). However, in patch-burning, the grazer attraction to the recently burned patch and 'grass banking' in the longer time since fire patches stabilizes livestock performance when precipitation is limited (Allred et al., 2014; Spiess et al., 2020).

While we add novelty to existing literature on livestock weight gains under patch-burning, some gaps are apparent in our knowledge of patch-burning on livestock performance. Firstly, because there is evidence that under long-term patch-burning, livestock performance exceeds conventional grazing (Limb et al., 2011). Future studies should consider long-term trends. Weights throughout the grazing season should also be considered to examine how temporal trends of forage nutritive value and forage biomass are influencing weight gain.

Conservation-based rotation grazing methods have been promoted in recent years to increase biodiversity and wildlife habitat (Derner et al., 2009; Milligan et al., 2020; Toombs et al., 2010). However, we recognize that conservation and individual animal performance are often not the primary goals of many rotational grazing systems (Jones and Sandland, 1974). Rotational grazing systems that are adaptive to temporal plant nutritive value patterns and planning rotations to capitalize on high quality forage regrowth may produce better weight gains compared to conservation-based systems (Derner et al., 2021; Teague et al., 2013). However, in our study, as in many areas of public lands, the goal of our study was to create heterogeneity in vegetation structure for conservation benefits with the rotational and patch-burn grazing strategies. If a land manager or producer's goal is to manage for both production and environmental sustainability, patch-burning is a favorable option since it does not negatively affect livestock gains and decreased annual variability of cow gains.

Conclusions

Livestock weight gain performance has a large impact on producer profitability, and to be sustainable grazing practices should benefit both ecosystem functionality and livestock production. Our study provides further insight into livestock performance under patch-burn grazing and is the first to compare patch-burn grazing to conservation-based rotational grazing. Factors that influence livestock performance, such as stocking rate, grazing intensity, forage nutritive value, forage biomass, and precipitation are complex and often intertwined. Several factors could be influencing our results. Patch-burn grazing appears to have a positive influence on at least some of these factors. Producers can use patch-burn grazing as a management practice to benefit species conservation while maintaining livestock weight gains. If conservation is the main goal, patch-burn grazing might be the optimal choice than conservation-based rotational grazing for maintaining livestock production while implementing a heterogeneity focused management strategy.

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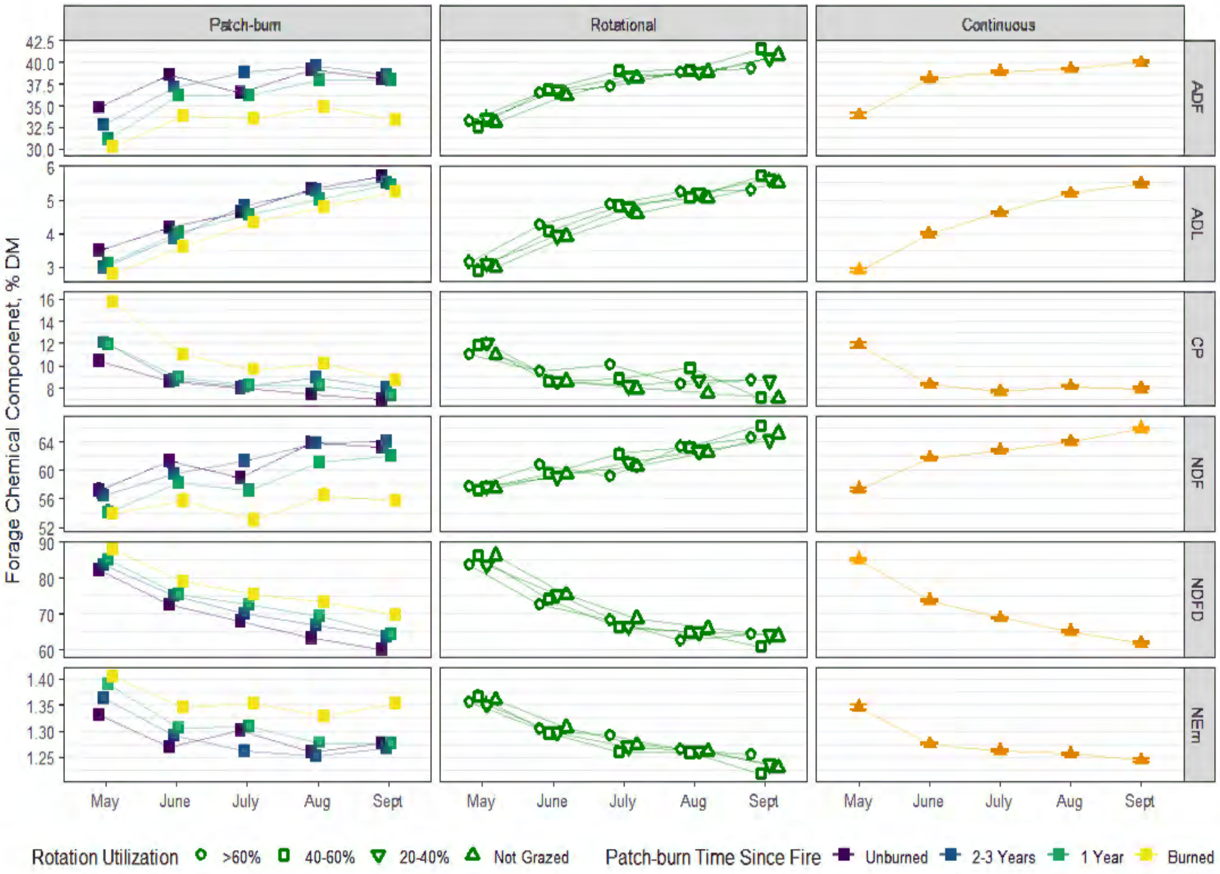
APPENDIX A: CLIPPING POINTS FOR FORAGE SAMPLING IN THE CONTINUOUS ROTATIONAL AND PATCH-BURN GRAZING STRATEGIES

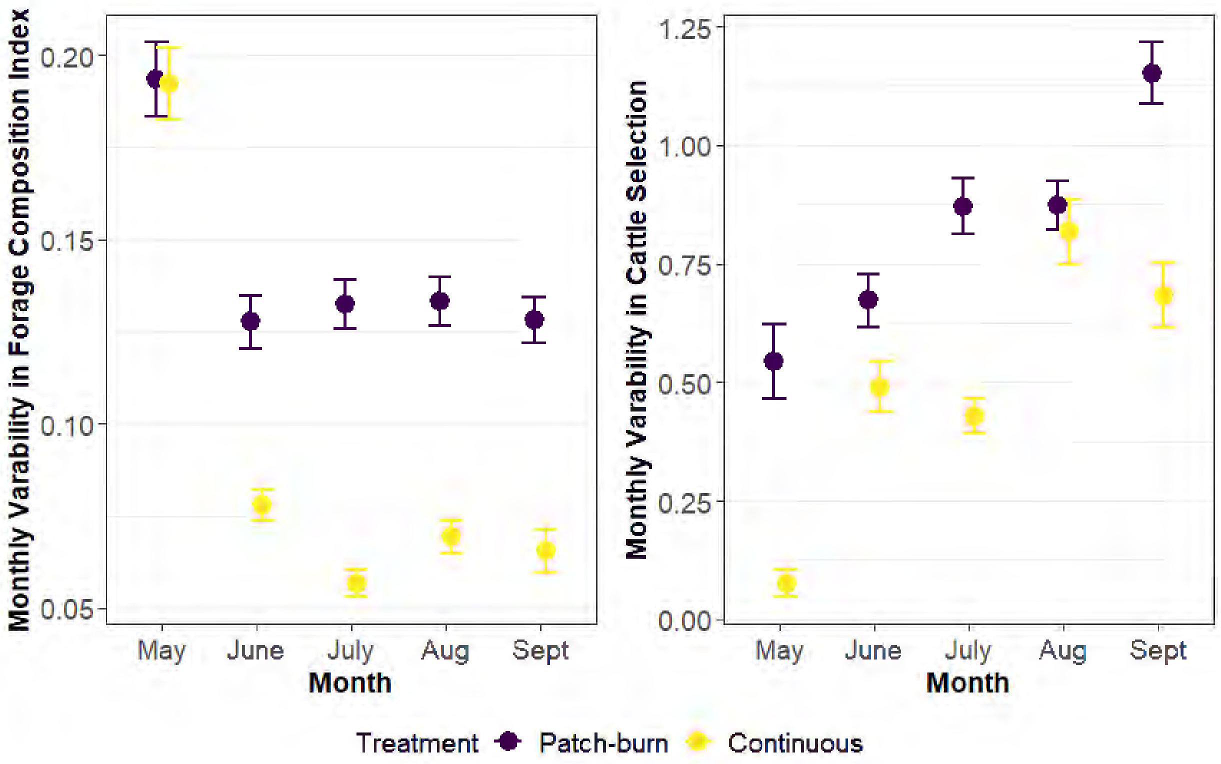
Sampling points for one replicate of each grazing strategy (a: continuous grazing, b: rotational grazing, c: patch-burn grazing). Yellow points on the diagrams indicate the sampling points that were returned to each month of the grazing season throughout the duration of the study. The green lines in figure b designate fences between the different paddocks of rotational grazing system. The blue outline in figure c indicates exterior fencing of the patch-burn grazing and pink lines separating each of the burn patches.

APPENDIX B: FORAGE NUTRIENT CONTENT BY MONTH FOR EACH GRAZING STRATEGY SPLIT BY TIME SINCE FIRE AND ROTATION UTILIZATION LEVEL



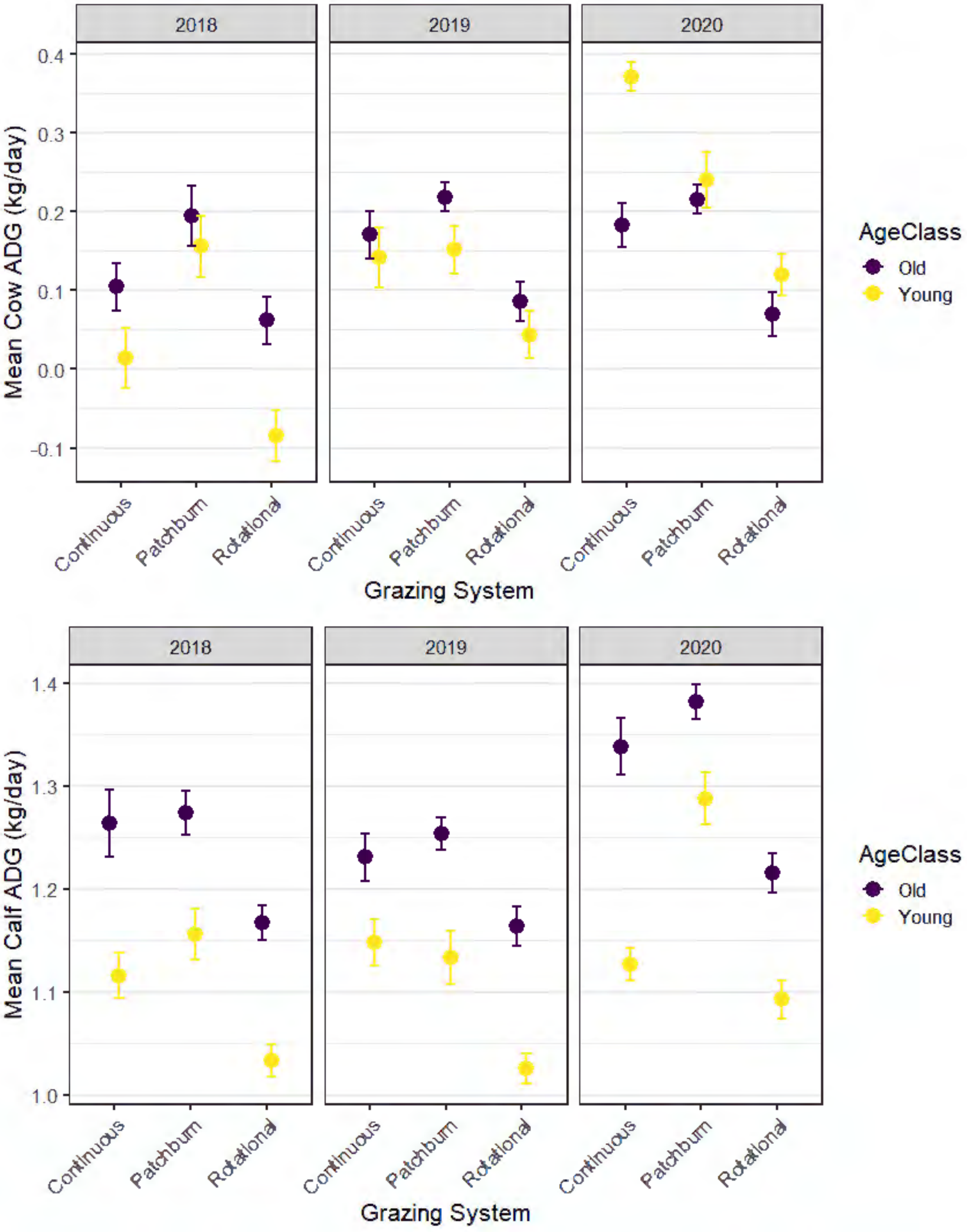
Monthly forage nutrient content for each grazing system with patch-burning split by time since fire and the rotational system split by utilization. The heavy use cell is >60% utilization, full use is 40-60%, moderate use is 20-40%, and rested is not grazed. ADF: acid detergent fiber, ADL: lignin, CP: crude protein, NDF: neutral detergent fiber, NDFD: neutral detergent fiber 24-hour digestibility, NE_m: net energy for maintenance.

APPENDIX C: FORAGE COMPOSITION INDICATOR AND CATTLE SELECTION VARIABILITY BY MONTH



Monthly variability in forage composition indicator and cattle selection by month for patch-burn and continuous grazing. Forage composition indicator is displayed in the figure on the left. Cattle selection is displayed in the figure on the right. Patch-burn is indicated by purple points and continuous grazing by the yellow points.

APPENDIX D: COW AND CALF AVERAGE DAILY GAIN BY YEAR



Mean cow and calf average daily gain (ADG) by grazing strategy, year and age class. Cow ADG is displayed in the top set of figures and calf ADG is displayed in the bottom set of figures. Yellow indicates young age class cows and purple indicates mature age class cows. Young age class cows in continuous grazing in 2020 have much higher ADG compared to the other years.