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Original Research

Grazing Preferences and Vegetation Feedbacks of the Fire-Grazing Interaction in the Northern Great Plains

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ABSTRACT

The fire-grazing interaction is well studied in mesic grasslands worldwide, but research is limited in semiarid systems. We examined the principal drivers and feedbacks of the fire-grazing interaction on the strength of cattle grazing selection, herbaceous biomass, crude protein, and vegetation structure and composition in two pastures in the Northern Great Plains. Cattle showed significant preference, use, and grazing utilization in recently burned patches that declined as time since fire increased. Cattle selection was driven by significantly increased crude protein in recent burns. Grazing utilization of 70% in patches with < 1 yr after fire established low herbaceous biomass, but the extent to which it was maintained varied with precipitation. Herbaceous biomass increased to nonburned levels 2 yr after fire, and crude protein decreased to nonburned levels 120 d after fire. Species composition was influenced primarily by site and year, though bare ground and litter were influenced by the fire-grazing interaction. Our data indicate that mixed-grass prairies of the Northern Great Plains are resilient to the fire-grazing interaction and that rest from grazing following fire is likely ecologically unnecessary. The use of the fire-grazing interaction is an alternative management strategy suitable for the Northern Great Plains, effectively increasing heterogeneity of grassland habitat.

Introduction

The coupled interaction of fire and grazing influences ecosystem structure and function of grasslands worldwide (Collins, 2000; Archibald et al., 2005; Murphy and Bowman, 2007; McGranahan et al., 2012). Research of the fire-grazing interaction has largely been in mesic (> 600-mm annual precipitation) grasslands and savannas (Fuhlendorf and Engle, 2004; Sensenig et al., 2010). In semiarid grasslands, where vegetation productivity is reduced and high topoedaphic variability exists, the strength and effects of the fire-grazing interaction may be reduced or lessened, evidenced by declines in grazing preference for burned areas and vegetative response (Augustine and Derner, 2014). The large spatiotemporal variability in precipitation of semiarid grasslands will also impact fire occurrence through fuel loadings and herbivore preference through vegetation regrowth (Knapp and Smith, 2001; Bennet et al., 2003). Although potentially reduced when compared with more mesic grasslands, the fire-grazing interaction can be an important driver of semiarid grassland structure and function (Augustine et al., 2010; Winter et al., 2011; Augustine and Derner, 2015).

Patch burn grazing is a management strategy used across many mesic grasslands that employs the fire-grazing interaction to mimic historical disturbances and processes (Ricketts and Sandercock, 2016). Fire is applied to spatially distinct sections of a management unit (hereafter referred to as *patches*) through time (Fuhlendorf and Engle, 2001). Cattle prefer recently burned areas and concentrate grazing therein while avoiding or not selecting other areas with greater time since fire (Allred et al., 2011; Fuhlendorf and Engle, 2004). This continuum from recently burned and grazed to nonburned and nongrazed results in a shifting mosaic with defined vegetation contrasts, increasing landscape heterogeneity (Fuhlendorf and Engle, 2004). While providing numerous conservation benefits (Fuhlendorf et al., 2006; Cummings et al., 2007), patch burn grazing can also be advantageous to livestock management, maintaining weight gains of yearling cattle at neutral to positive levels with improved stability through time (Allred et al., 2014; Limb et al., 2011).

Grasslands across North America have declined to < 20% of their historic area (Knopf, 1994; Noss et al., 1995). The Northern Great Plains is one of the last remaining, large intact prairies in North America (Cooper et al., 2001). Despite the large intact landscape, the Northern Great Plains faces numerous threats. Agricultural conversion continues to occur (Lark et al., 2015), and energy development presents new challenges of fragmentation and sustainability (Fargione et al., 2012;

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Allred et al., 2015). Habitat loss and increased fragmentation are the primary factors impacting grassland functioning and wildlife species of conservation concern (Brennan and Kuvlesky, 2005; Sauer et al., 2015), along with the homogenization of vegetation structure resulting from human alterations to historical fire and grazing regimes (Askins et al., 2007; Derner et al., 2009). There is a need to explore alternative management strategies that couple interacting disturbances on the landscape, such as fire and grazing, to create habitat heterogeneity and maintain sustainable ranching.

An improved understanding of the fire-grazing interaction is needed to evaluate the utility of patch burn grazing in the Northern Great Plains. Previous research has largely excluded fire or decoupled the spatial and temporal feedbacks of the fire-grazing interaction. Although semiarid, the Northern Great Plains is a fire-adapted ecosystem (Whisenant and Uresk, 1989; Vermeire et al., 2011; Strong et al., 2013) resilient to both fire and grazing (Vermeire et al., 2014; Gates et al., 2017). Our goal was to examine the strength of fire-grazing interaction in the Northern Great Plains. We did not compare the fire-grazing interaction with other management strategies, but rather directly examined the principal drivers and feedbacks of grazing and vegetation responses within the interaction. Our specific objectives were to quantify 1) cattle grazing preferences, use, and grazing utilization of burned patches; 2) herbaceous biomass and crude protein; and 3) vegetation structure and composition.

Methods

Study Site

We examined the fire-grazing interaction at The Nature Conservancy—owned Matador Ranch (12 545 ha) in northeast Montana. The terrain is primarily undulating hills characteristic of the Great Plains with slopes ranging from 0% to 35% at an average elevation of 932 m. The region was glaciated during the Pleistocene and is underlain with sandy silts in upper ridges and clayey loams in lowlands. Moisture availability and soils create two contrasting ecological sites differing in vegetation composition and productivity, mesic lowlands and drier uplands. Soils have relatively low productivity given thin top soils on top of crushed limestone. The plant community is a mixed-grass prairie dominated by cool-season perennial grasses, mainly wheatgrass-needlegrass *(Pascopyrum-Hesperostipa)* communities, along with interspersed forbs and subshrubs. Graminoids include threadleaf sedge (*Carex filifolia* Nutt.), needle-and-thread (*Hesperostipa comata* [Trin. & Rupr.] Barkworth), green needlegrass (*Nassella viridula* [Trin.] Barkworth), western wheatgrass (*Pascopyrum smithii* [Rydb.] A. Löve), prairie junegrass (*Koeleria macrantha* [Ledeb.] J. Schultes), crested wheatgrass (*Agropyron cristatum* [L.] Gaertner), Japanese brome (*Bromus japonicas* Thunb.), and Kentucky bluegrass (*Poa pratensis* L.). Primary forbs are common yarrow (*Achillea millefolium* L.) and hairy false goldenaster (*Heterotheca villosa* [Pursh] Shinners). Shrubs are composed of prairie sagewort (*Artemisia frigida* Willd.) and silver sagebrush (*Artemisia cana* Pursh.). The soil surface is often interspersed with club-moss (*Selaginella densa* Rydb.). Total growing season precipitation (April—September) was 251 mm at 92% of the 30-yr average in 2015 and 480 mm at 176% in 2016 (Fig. 1; PRISM, 2017).

Study Design

Prescribed fire was conducted in two pastures before the arrival of spring precipitation in late March or early April (Fig. 2). Different sections of pasture A (355 ha) were burned consecutively from 2014 through 2016 with patches varying in proportion of pasture area from 20—40%. Due to unfavorable weather conditions, pasture B (533 ha) only had a single burn in 2015 (encompassing 10% of pasture area), reducing our burn sample size. Though moderate fuel loads were present, burns were often patchy in nature due to topography and disruptions in fuel continuity created by inherent productivity and rocky areas where vegetation was absent. These pastures had not been burned for at least 20 yr before this study. Rotational grazing was used at moderate stock densities in both pastures during the early growing season, approximately 2 mo after fire and after vegetation had initiated regrowth in the most recent burned patch. Pasture A was grazed at a stock rate of 1.10 animal unit month (AUM) ha^{-1} from June 2 to 17 and May 16 to June 11 in 2015 and 2016, respectively. Pasture B was grazed at a stock rate of 0.65 AUM ha^{-1} from June 8 to July 1 and May 16 to June 11 in 2015 and 2016, respectively. Water for livestock was widely available across both pastures with equal access in all burned and nonburned patches.

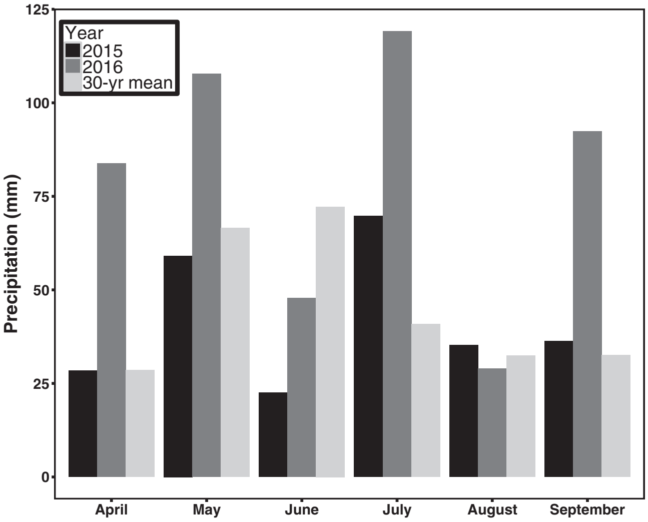

Figure 1. Total monthly precipitation during the growing season (April—September) at The Nature Conservancy Matador Ranch in northeast Montana during 2015 (251 mm growing season total), 2016 (480 mm), and 30-yr average (271 mm) (PRISM Climate Group).

Data Collection

Cattle Selection

Cattle grazing preferences were quantified through visual inspection, dung pats, and grazing utilization. Visual inspection included counting the number of individual cattle in each distinct burn patch at random time intervals (> 3 hr apart for independence) from 6:00 am through 9:00 pm each day (three to five observations per day). Individual cattle were counted in each patch during observations rather than the number of groups as high variation occurs in group size (Coppedge and Shaw, 1998). A selectivity index (SI) was used to account for variation in patch size in determining the strength of cattle patch preferences (Vinton et al., 1993; Schuler et al., 2006). The SI was calculated as the percentage of total cattle counted in a patch divided by the proportion of pasture area encompassed by the patch. SI values of 1 indicate even distribution of cattle across the pasture, while values above 1 show patch preference and values below 1 show avoidance. In addition to the SI, patch preference for recent burned patches was indexed by the percentage of total cattle counted inside of patches across both years, permitting comparison with other studies. Patch 4 was excluded from this percentage analysis, as it comprised only 10% of pasture area and was not comparable with other studies with patches comprising a greater proportion pasture area (25—33% pasture area). We also quantified cattle use by counting fresh cattle dung pats along twelve (45 × 4 m) belt transects in each patch (Archibald et al., 2005; Barnes, 2001). Dung pats were identified as fresh if deposited during the same year as observation and were differentiated from dung pats deposited during previous years by having greater moisture content and less viscosity. Lastly, we constructed grazing exclosures to measure grazing utilization. Utilization was determined after cattle had left pastures by harvesting aboveground standing biomass (live and dead) using a 0.25-m^2 frame

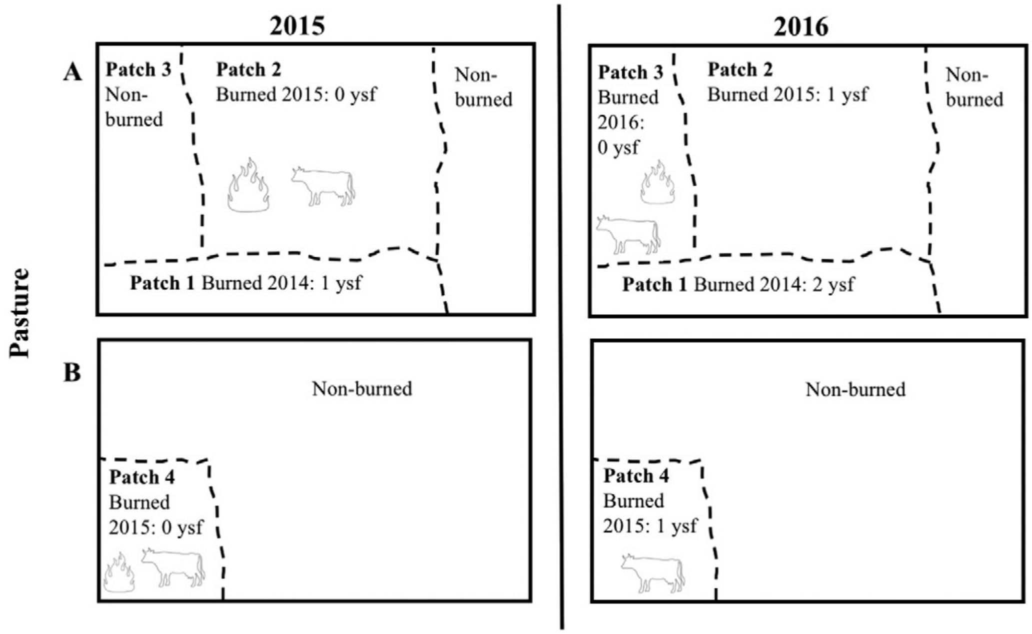

Figure 2. Fire-grazing interaction study design in the Northern Great Plains for yr 2015 and 2016. Pasture **A** (355 ha) contained three burned patches comprising 20 – 40% of pasture area, along with nonburned areas. Pasture **B** (533 ha) contained a single burned patch comprising 10% of pasture area and nonburned areas. Patch sizes and configurations are drawn approximately to scale. Water was widely available across both pastures with equal access for cattle in all burned and nonburned patches. *Solid lines* indicate pasture fence boundaries; *dotted lines* indicate patch location of fires. Years since fire (ysf) of patches is indicated. Flame and cattle represent location of current years' burn with increased cattle utilization. Due to unfavorable conditions, we were not able to burn pasture B in 2016.

in grazing exclosures and paired grazed sites in four different locations per patch. Biomass samples were oven dried at 50°C for 72 hr and weighed; utilization was calculated as the difference in biomass from within and outside of exclosures.

Herbaceous Biomass and Crude Protein

We harvested aboveground standing herbaceous biomass (live and dead) using a 0.25-m^2 frame from 15 different locations within each patch from May to August during 10 sampling periods in 2015 and 11 in 2016. Sampling occurred weekly during grazing and then biweekly thereafter. Biomass samples were oven dried at 50°C for 72 hr and weighed. Three biomass samples per patch were analyzed for crude protein (%) at biweekly intervals from seven sampling periods in 2015 and eight in 2016. Crude protein (%) was determined using a dry combustion analyzer (LECO Corp., St. Joseph, MI).

Vegetation Structure and Composition

We examined vegetation composition and structure in each patch after grazing during July in both years. The line point intercept method was used to determine the percent cover of plant functional groups, bare ground, soil, and litter (Herrick et al., 2009). Plant functional groups included forbs, club-moss *(Selaginella densa)*, shrubs, sedges, and grasses. Ten transects 20 m in length were established in each patch and sampled every 0.5 m. Bare ground was recorded when the following occurred: no top canopy present, no litter or plants in lower canopy levels, and only soil at ground surface. Soil was recorded when bare soil was present at the ground surface, regardless of plant cover. Litter was recorded when dead plant material was lying horizontally on the ground surface.

Data Analysis

Linear regressions were used to test relationships of the selectivity index, aboveground biomass, and crude protein with time since fire in burned patches. A one-way analysis of variance (ANOVA) was used to test for the effects of time since fire (measured in years) at the patch level on cattle dung pats and grazing utilization. A post hoc Tukey test was used for pairwise comparisons across the annual gradient of time since fire. All analyses were conducted using R (R Development Core Team, 2016). An indirect gradient analysis using Detrended Correspondence Analysis (DCA) was conducted on vegetation functional groups at the transect level with the DECORANA function in the R package Vegan (Oksanen et al., 2016). Sampling locations (transects) or site scores were arranged in DCA on the basis of variation in species composition and abundance, reflecting overall environmental variation. The influence of individual variables on the total ecological variation expressed across species and transects was determined from loading scores generated by DCA. Variables were plotted along two axes based on two sets of loading scores with distances between variables representative of ecological distances, similar variables being located closer together. Linear regressions were used to test relationships between DCA loading scores and year, time since fire, and patch location.

Results

Cattle Selection

Cattle showed strong selection for recently burned patches along the gradient of time since fire across the suite of selection metrics. Cattle grazed recently burned patches comprising approximately a quarter of pasture area 48% of the time. Cattle grazing preference for a given patch, represented by the selectivity index (SI), declined with years since fire (Fig. 3A). Average SI values ranged from 1.8 in recently burned patches to 0.7 in nonburned patches. SI values in recently burned patches were consistently > 1 during both years, indicating strong patch preference. Selection preferences varied between years; in 2015 preference for recently burned patches increased with week of year, while in 2016 it decreased. Preference for patches at 1 yr since fire and nonburned were lower in 2015 than 2016, corresponding with a higher selection occurring in recently burned patches. During 2016, SI values were the lowest across patches in the single patch at 2 yr since fire. Time since fire (weeks) of a patch and SI had a significant negative relationship across both years (see Fig. 3B, $P < 0.01$). Counts of fresh cattle dung pats significantly decreased as years since fire of a patch

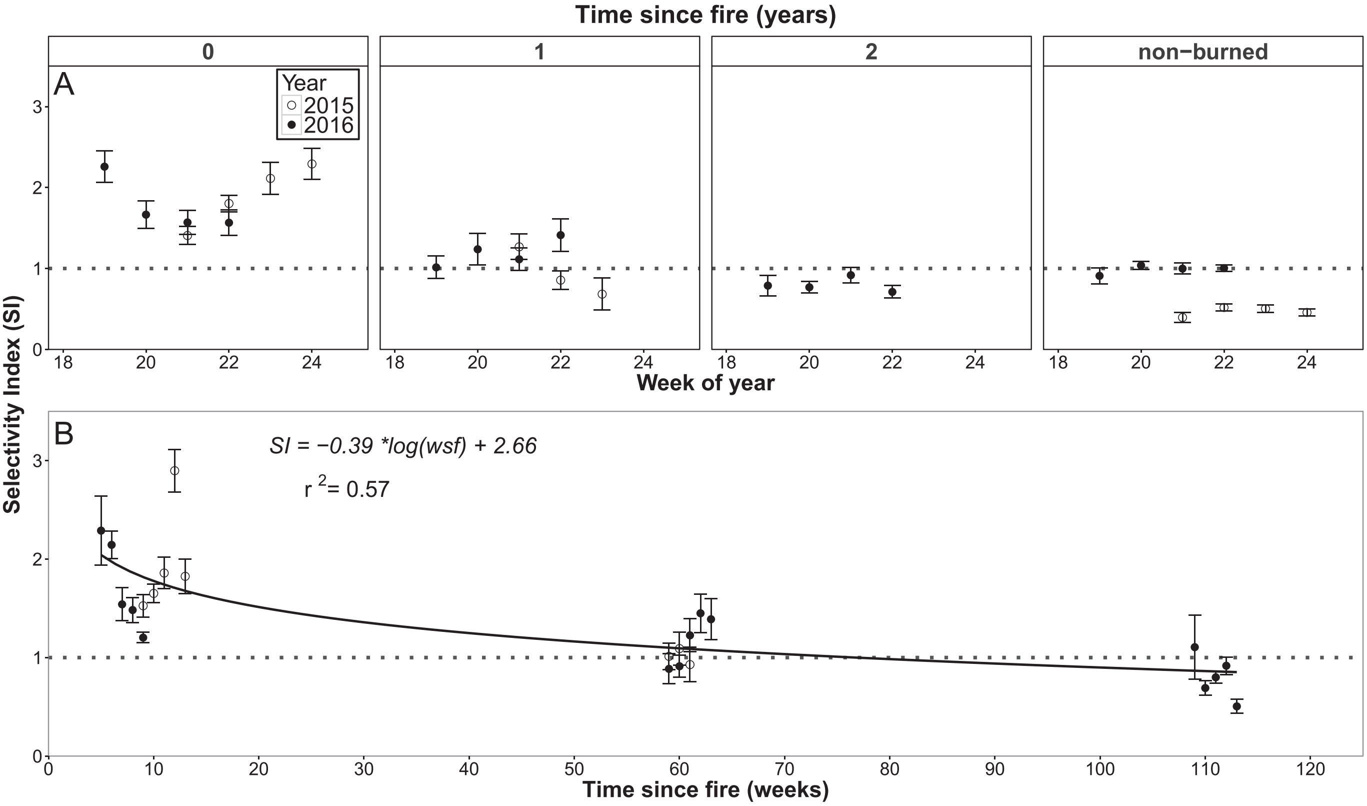

Figure 3. (**A**) Cattle grazing preferences for nonburned and burned patches varying in time since fire (years) during 2015 and 2016 in the Northern Great Plains plotted by week of year; grazing preferences expressed as a selectivity index (SI). Points represent weekly averages from multiple daily observations. *Dotted line* indicates preference threshold of 1 with SI values above indicating patch preference and below indicating avoidance. (**B**) Grazing preferences plotted by time since fire (weeks) of burned patches in 2015 and 2016. SI values had a significant negative relationship with the number of weeks since fire (wsf) ($P < 0.01$). Error bars represent one standard error.

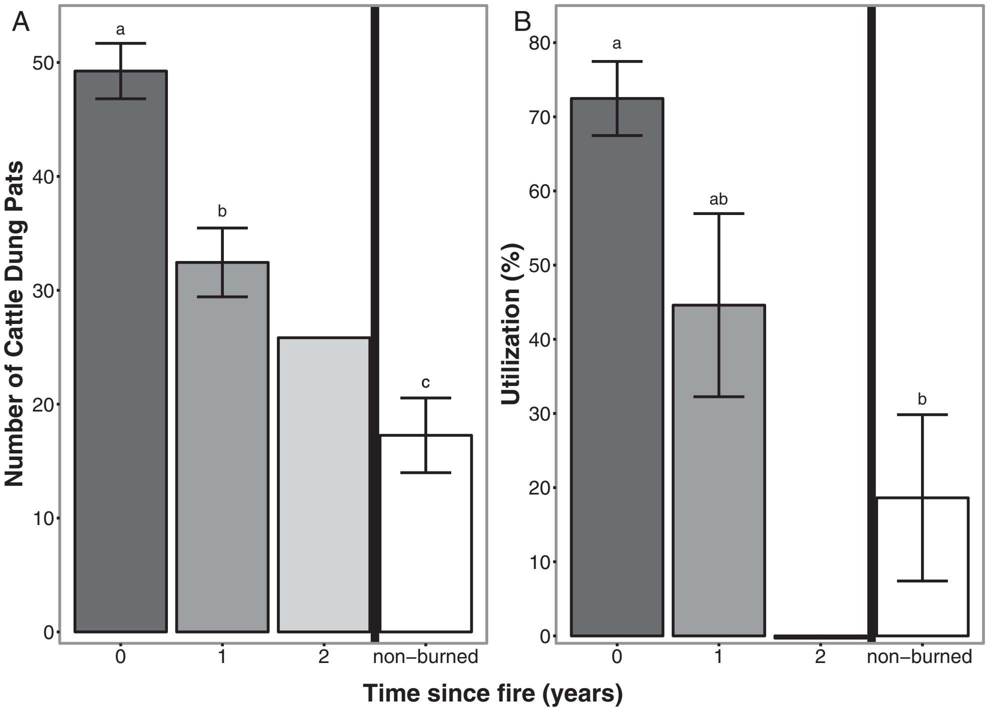

Figure 4. (**A**) Number of fresh cattle dung pats counted in nonburned and burned patches varying in time since fire (years) in the Northern Great Plains. Bars with different letters above them indicate significant differences ($P < 0.05$, Tukey's honestly significant difference test). Error bars represent one standard error. (**B**) Grazing utilization (%) for nonburned and burned patches varying in time since fire (years). Only one burn was available at 2 yr since fire, shown here for comparison only and excluded from analysis.

increased (Fig. 4A, $F_{2,6} = 29.76$, $P < 0.01$, ANOVA). Dung pats in the patch at 2 yr since fire followed the declining trend with greater time since fire but were excluded from the analysis since a single replicate. Cattle grazing utilization also significantly decreased with greater time since fire (see Fig. 4B, $F_{2,6} = 7.18$, $P < 0.05$, ANOVA). Utilization in recently burned patches was significantly greater than in nonburned patches ($P < 0.05$, Tukey's honestly significant difference [HSD] test). Nonburned patches received greater utilization than the single patch at 2 yr since fire, which had no utilization (value of 0) and was excluded from analysis as a single replicate.

Herbaceous Biomass and Crude Protein

Herbaceous biomass varied with time since fire and day of year (doy) (Fig. 5A). Biomass was the lowest in recently burned patches, though large fluctuations occurred across the growing season. Biomass in patches at 1 yr since fire was above recently burned patches and increased to nearly the same level as the patch at 2 yr since fire by the end of the growing season. Temporal fluctuations of biomass during the growing season differed between years. In 2015 biomass increased in all patches at the beginning of the growing season, though it declined across patches during grazing (doy 160) and increased in only nonburned patches following grazing (doy 180). At the end of sampling for each year, biomass was similar in patches at 1 yr since fire and recently burned, though still below nonburned patches. In 2016 large increases in biomass occurred in all patches as the growing season progressed, especially after grazing (doy 170). At the end of sampling in 2016, biomass was similar across patches, though still reduced in recently burned patches. The patch at 2 yr since fire contained similar levels of biomass as nonburned patches. Biomass in burned patches had a significant positive relationship with days since fire (see Fig. 5B, $P < 0.01$).

Crude protein in recently burned patches at the start of the growing season was nearly twice as high as patches with greater time since fire and nonburned (Fig. 6A). However, by the end of the growing season, crude protein had declined to similar levels across all patches, regardless of time since fire. Similar to biomass, large temporal variation in protein occurred between years. Higher crude protein occurred in 2016 for all patches with substantially higher levels in recently burned patches. No change in crude protein occurred following grazing in 2015, though it increased across patches following grazing in 2016 (doy 180). Crude protein in recently burned patches had a significant negative relationship with days since fire (see Fig. 6B, $P < 0.01$).

Vegetation Structure and Composition

The two axes of the DCA accounted for 18% of the variance in vegetation data. On DCA axis 1, the order of influence by dominant functional groups was club-moss *(Selaginella densa)*, soil, bare ground, and sedges (Fig. 7A). On DCA axis 2 the order of influence was bare ground, litter, forbs, and moss. Transect variability (i.e., site scores) on DCA axis 1 was significantly influenced by years since fire, though weakly correlated (see Fig. 7B, $P < 0.01$, $r^2 = 33\%$). Transect variability on axis 1 was strongly correlated and significantly influenced by patch location ($P < 0.01$, $r^2 = 57\%$). There was no clear correlation for transect variability on axis 2 with environmental variables or time since fire.

Discussion

The ecological interaction between fire and grazing is clearly present in the Northern Great Plains; however, this interaction may be weaker than in mesic grasslands as productivity is decreased and tightly regulated by topoedaphic variability. Feedbacks between time since fire and cattle grazing selection are coupled and consistent in the Northern

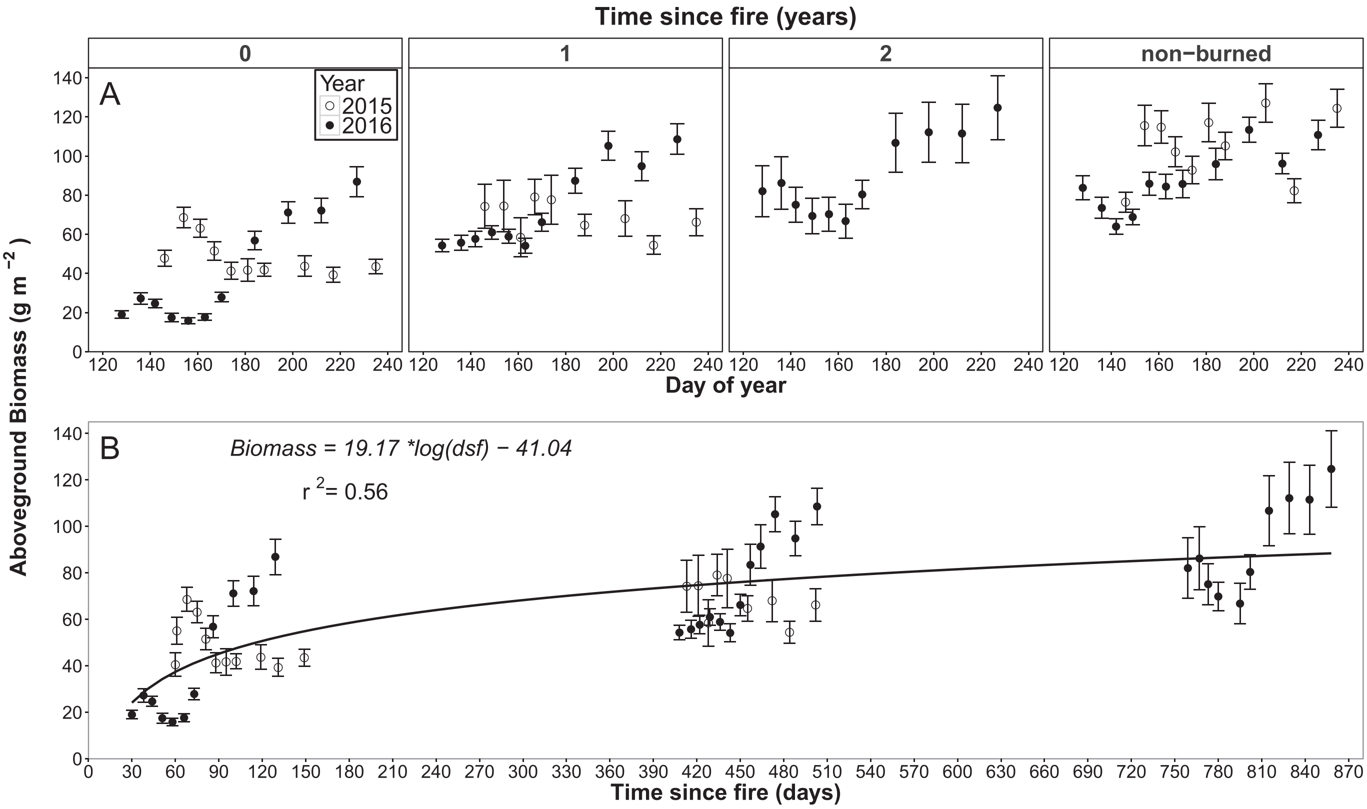

Figure 5. (**A**) Aboveground biomass (g m^{-2}) by day of year through the growing season (May—August) in nonburned and burned patches varying in time since fire (years) in the Northern Great Plains. (**B**) Aboveground biomass by time since fire (days) of burned patches across the study period. Aboveground biomass sampled in burns had a significant positive relationship with the number of days since fire (dsf) ($P < 0.01$). Error bars represent one standard error.

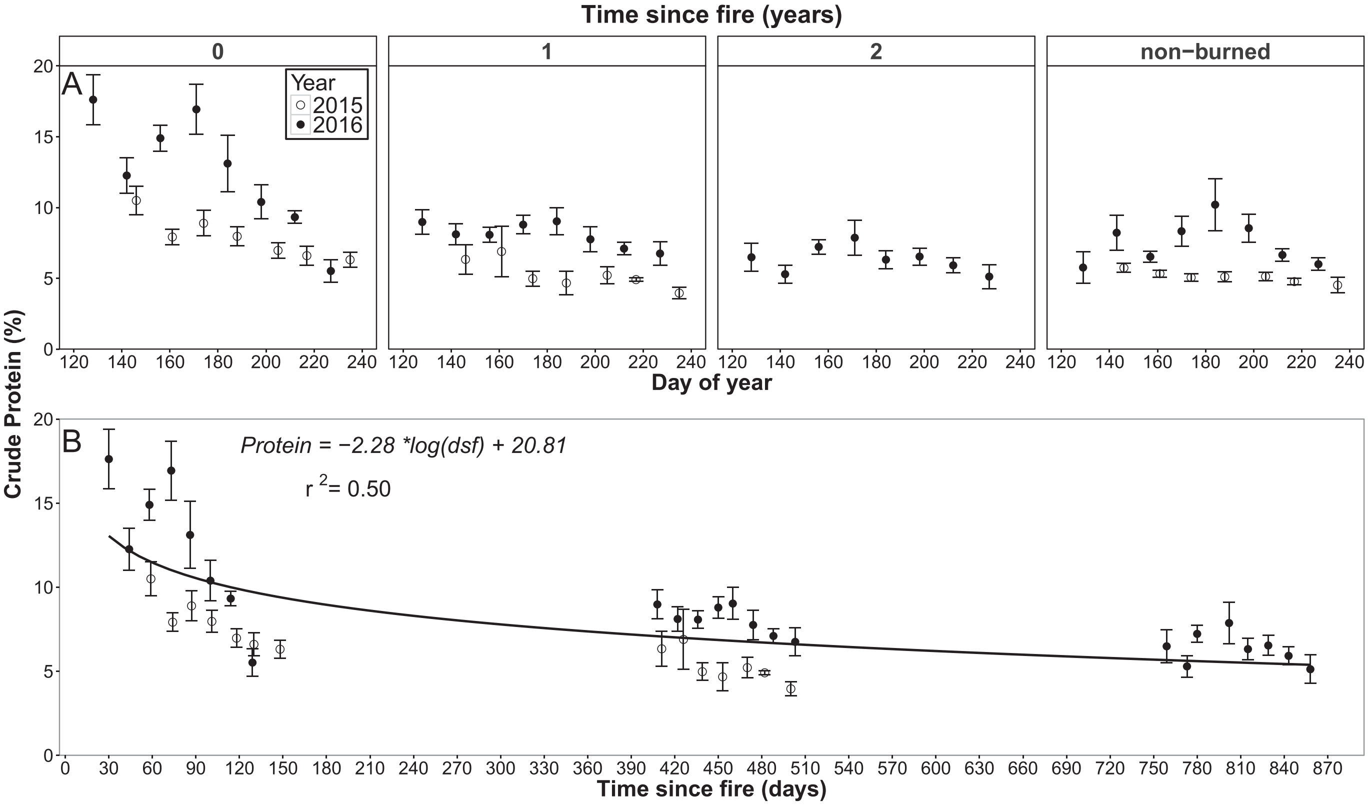

Figure 6. (**A**) Crude protein (%) of biweekly harvested standing herbaceous biomass by day of year across the growing season (May — August) in nonburned and burned patches varying in time since fire (years) in the Northern Great Plains. (**B**) Crude protein (%) by time since fire (days) of burned patches across the study period. Protein in burned patches had a significant negative relationship with the number of days since fire (dsf) ($P < 0.01$). Error bars represent one standard error.

Great Plains, primarily driven by responses in crude protein. Cattle preferentially grazed recently burned patches over others with greater time since fire, as demonstrated in mesic grasslands (Allred et al., 2011). Herbaceous biomass did not appear to be a mechanism of selection as cattle consistently grazed recently burned patches with substantially reduced biomass (20 g m^{-2}), similar to the shortgrass prairie (21 g m^{-2}) (Augustine and Derner, 2014). Rather, changes in grazing selection aligned with improved crude protein regardless of reductions in biomass, as demonstrated in grasslands worldwide (Murphy and Bowman, 2007; Sensenig et al., 2010; Eby et al., 2014).

The persistence of feedbacks between fire and grazing selection across the Great Plains is likely influenced by the magnitude of increase in crude protein in recently burned patches compared with nonburned patches. Both cattle burn preference (grazing recently burned patches 75% of the time) and protein increase (450%) in the tallgrass prairie (Fuhlendorf and Engle, 2004; Allred et al., 2011) are roughly 2.3-fold greater than cattle burn preference (grazing recent burned patches 31% of the time) and crude protein increase (200%) in the shortgrass prairie (Augustine and Milchunas, 2009; Augustine and Derner, 2014). Cattle burn preference in the Northern Great Plains (48%) is roughly 1.5-fold above the shortgrass and below the tallgrass by the same margin. Crude protein increase in the Northern Great Plains (350%) is approximately 1.75-fold greater than the shortgrass and 1.3-fold less than the tallgrass. This suggests that cattle grazing selection likely corresponds with the response of crude protein to fire across the Great Plains.

Both cattle dung pats and grazing utilization indicate that cumulative patch use is similarly increased in recently burned patches, as shown at shorter observational periods with cattle preferences calculated with the SI. Both cattle dung counts and grazing utilization were nearly threefold higher in recently burned patches compared with nonburned patches and declined with greater time since fire (Fig. 4). Grazing utilization did not follow as clear of a trend with time since fire as dung counts since utilization for the patch at 2 yr since fire was below nonburned patches with a value of zero. Both SI and grazing utilization indicate that cattle showed lower grazing preference for the patch at 2 yr since fire than all other patches (see Figs. 3A, 4A), likely due to the patch containing the least amount of crude protein across patches (Fig. 6A). However, dung counts indicate that cattle spent more time in this patch than nonburned patches, as dung counts also reflect time spent walking and resting. Unfortunately, weather conditions did not permit burning in pasture B during 2014 and 2016. Pasture B contained only a single burn that ranged from zero to 1 yr since fire throughout the study. This created an opportunity to examine cattle selection for a single burn patch in a pasture compared with the other pasture containing a mosaic of burn patches. In 2015 all three metrics of cattle selection in recently burned patches did not vary between pastures. However, in 2016 cattle exhibited stronger selection along all three metrics for patches at 1 yr since fire in pasture B, demonstrating that cattle strongly select burn patches even after 1 yr since fire within a nonburned landscape.

The fire-grazing interaction produced only short-term changes in biomass in the Northern Great Plains and did not override climate and topoedaphic regulators of productivity (Burke et al., 1999; Dodd et al., 2002). The strong positive log relationship between biomass and days since fire reflects increased plant growth during the first growing season post fire with growth declining in subsequent years. In a year with average precipitation, low biomass in recently burned patches was maintained after grazing for the remainder of the growing season. However, in 2016 biomass increased following grazing with precipitation at nearly triple the monthly average in July, supporting that precipitation is a dominant driver of productivity in the Northern Great Plains (Wiles et al., 2011). Reduced variance in harvested biomass occurred in

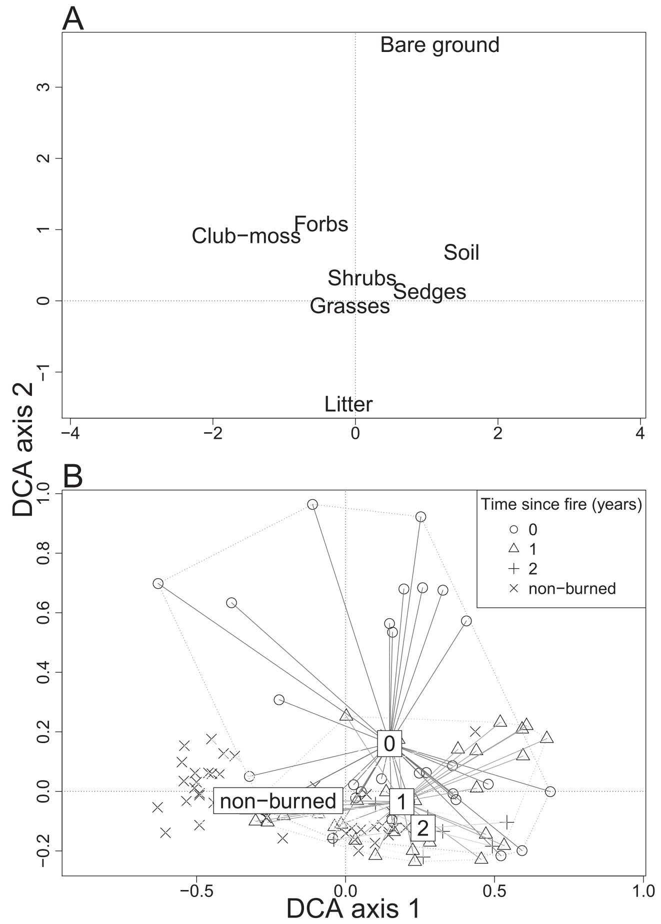

Figure 7. Plots of the first two axes of the detrended correspondence analysis for vegetation structure in nonburned and burned patches varying in time since fire (years) in the Northern Great Plains. (**A**) Species scores for plant functional groups, along with litter and bare ground; (**B**) Site scores for individual transects in nonburned and burned patches varying in time since fire (years), spindles connecting transects and envelopes around transects indicate time since fire (years).

recently burned patches, likely as a result of shifted grazing selection from particular species to the patch. Vegetation heterogeneity is similarly reduced within recently burned patches in mesic grasslands, as grazing pressure is decreased at a species level and spread across the entire patch (Archibald and Bond, 2004; Parrini and Owen-Smith, 2009). The fire-grazing interaction in the Northern Great Plains increased vegetation heterogeneity at the larger pasture scale. Similar to other grasslands, focal grazing in recent burned areas resulted in low levels of biomass while the lack of grazing elsewhere permitted biomass to accumulate. As a result, the fire-grazing interaction created a gradient of increasing biomass with greater time since fire, creating heterogeneity in vegetation structure. However, fluctuations in precipitation limited the degree of contrast established between patches and the temporal extent that heterogeneity was maintained.

Increased crude protein occurred in recently burned patches as a result of vegetation regrowth containing young tissues high in nitrogen (Van deVijver et al., 1999; Sensenig et al., 2010; Eby et al., 2014). The strong negative log relationship between days since fire and crude protein demonstrates that enhanced crude protein in recently burned patches occurs for only a short timeframe in the first half of the growing season before declining as biomass increases. Crude protein declines with tissue maturation as the growing season progresses (McNaughton, 1985); however, the fire-grazing interaction slows down the rate of decline in recently burned patches compared with other patches with greater time since fire. Enhanced crude protein in recently burned patches was maintained above 10% during the first half of the growing season.

Similar to other semiarid regions, the fire-grazing interaction had little influence on plant species composition (Vermeire et al., 2014; Gates et al., 2017), demonstrating resilience to fire and grazing. Relatively similar transect locations in the DCA indicate close ecological distances between plant functional groups. However, a gradient was present on the DCA plot (see Fig. 7B) with nonburned transects on the left and burned patches on the right. Transects in burned patches followed a downward gradient with increasing time since fire, reflecting slight changes in vegetation as it quickly returned to a nonburned state with reduced grazing utilization. Functional groups related to the ground surface (club-moss, soil, and bare ground) showed the greatest variation on DCA axis 1, which was influenced by patch location, reflecting variation in soils and topography. The variation was also explained to a lesser extent by time since fire as the ground surface is sensitive to the combined disturbances of fire and grazing. Variation on DCA axis 2 was weakly explained by the full gradient of time since fire because variability due to the fire-grazing interaction is only detectable during the immediate growing season post fire, as the mixed-grass prairie is resilient to disturbance (Gates et al., 2017). However, large variability occurred with litter and bare ground across sites on DCA axis 2 as fire and subsequent grazing influence both variables in recently burned patches.

Management Implications

Only 20% of the once extensive grasslands across North America remain (Samson and Knopf, 1994; Noss et al., 1995), and as a result proper grazing management is vital for conservation across the region to sustain ecosystem structure and processes. Patch burn grazing is an effective management tool to create habitat heterogeneity and realigns cattle grazing with historical disturbance regimes. Stocking rates can be adjusted in the Northern Great Plains to influence large-scale vegetation heterogeneity; however, environmental constraints limit the degree to which vegetation contrasts are established and maintained (Lwiwski et al., 2015; Lipsey and Naugle, 2016). Manipulation of stocking rates alone may not be enough to create habitat heterogeneity at the local scales needed for songbird species of conservation concern. Some songbirds prefer sparse cover, such as the McCown's Longspur *(Rhynchophanes mccownii)*, while others prefer dense cover, such as the Grasshopper sparrow *(Ammodramus savannarum)*, with other species selecting cover levels in between (Lipsey and Naugle, 2016). Patch burn grazing alters vegetation cover at multiple spatial scales and can benefit a suite of birds as habitat ranges from sparse to dense cover in relation to time since fire. As climate in the Northern Great Plains becomes more variable with increased precipitation (Millett and Johnson, 2009; Kunkle et al., 2013), patch burn grazing may also be used to maintain heterogeneity on the landscape when vegetation growth surpasses grazing utilization (Lipsey and Naugle, 2016), as well as stabilize livestock productivity (Allred et al., 2014).

The recovery of vegetation to nonburned levels 2 yr after fire and grazing demonstrates that the mixed-grass prairie of the Northern Great Plains is resilient to the fire-grazing interaction as in other semiarid grasslands. Similar to Gates et al. (2017), our results indicate that rest periods from grazing following fire are likely ecologically unnecessary in the Northern Great Plains. The shift in cattle grazing preferences in response to fire in the mixed-grass prairie also supports the use of burning to attract livestock and other herbivores into areas that typically receive little use as demonstrated in other grasslands (Bailey, 2004; Augustine and Derner, 2015). Enhanced crude protein in recently burned patches may also benefit cattle during the early growing season. Although the fire-grazing interaction in the Northern Great Plains is a significant top-down influence on forage quantity and crude protein in the months following fire, plant communities are still primarily regulated by climate and topoedaphic factors.

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