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DRIVERS AND FEEDBACKS OF THE FIRE-GRAZING INTERACTION IN THE NORTHERN GREAT PLAINS

By

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

Chairperson: Dr. Brady Allred

The fire-grazing interaction is well studied in mesic grasslands worldwide, but research is lacking in semiarid systems. In addition, the fire-grazing interaction reduces the invasion of exotic forage species in mesic grasslands by increasing the scale of grazing selection and may be a tool to control invasive plants in other grasslands. We examined the principal drivers and feedbacks of the fire-grazing interaction on the strength of cattle grazing selection, forage quantity and quality, and vegetation structure and composition in two pastures in northeast Montana at The Nature Conservancy's Matador Ranch. We also determined the influence of time since fire, within the context of the fire-grazing interaction, on cover and herbicide efficacy of crested wheatgrass (*Agropyron cristatum* [L.] Gaertner), an introduced perennial grass with numerous negative impacts on grassland habitat. Cattle showed significant preference, use, and grazing utilization in recent burned patches that declined as time since fire increased. Cattle selection was driven by significantly increased forage quality in recent burns. Cattle established low forage quantity in recent burned patches, but the extent to which it was maintained varied with precipitation. Forage quality decreased with time since fire as forage quantity increased. Forage production returned to unburned levels after two years since fire, demonstrating that the mixed grass prairie is resilient to the fire-grazing interaction. Species composition was influenced primarily by site and year, though bare ground and litter were influenced by the fire-grazing interaction. The fire-grazing interaction shifted grazing preferences from being plant specific to patch specific in recent burns. The fire-grazing interaction maintained stable cover of *A. cristatum* in recent burned patches while it increased two fold elsewhere. Herbicide substantially reduced cover of *A. cristatum* regardless of years since fire, though plant mortality at the larger plot scale decreased with time since fire. The fire-grazing interaction alone may be a viable treatment option for small infestations of crested wheatgrass in native rangelands that utilizes the available forage base and reduces the economic and ecological costs of herbicide. In addition, the gradient of grazing utilization may enhance the effectiveness of cattle as ecosystem engineers of grassland habitat.

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Introduction

The coupled interaction of fire and grazing influences ecosystem structure and function of grasslands worldwide (Archibald et al., 2005; Collins, 2000; McGranahan et al., 2012; Murphy and Bowman, 2007). This interaction drives grassland productivity and biodiversity at multiple trophic levels, providing greater effects than fire or grazing alone (Archibald et al., 2005; Benton et al., 2003; Collins, 1992; Fuhlendorf and Engle, 2001; Hovick et al., 2015). Increased plant growth occurs in recently burned areas, responding to changes in nutrient cycling and light limitations (Augustine et al., 2010; Blair, 1997; Johnson and Matchett, 2001). As a result, herbaceous vegetation regrowth in burned areas is high in protein (Eby et al., 2014; Sensenig et al., 2010; Van deVijver et al., 1999), which attracts a diversity of wild and domesticated herbivores (Klop et al., 2007; Moe and Wegge, 1997; Murphy and Bowman, 2007; Ónodi et al., 2008; Pearson et al., 1995; Sensenig et al., 2010; Vinton et al., 1993). The increased grazing of burned areas removes aboveground biomass (fuel), decreasing the probability of future fires (Leonard et al., 2010). Grazing of burned areas declines with time (Allred et al., 2011), allowing aboveground biomass to accumulate, increasing the probability of fire. These feedbacks interact with broader spatial patterns defined by climate and soil distribution (Du Toit et al., 2003) to establish and maintain the fire-grazing interaction. The resulting patchwork of burned/grazed and unburned/ungrazed areas, defined primarily by the amount of time since fire, creates a shifting mosaic of vegetation structure and composition mimicking historical disturbances (Askins, 2002; Brennan and Kuvlesky, 2005).

Research of the fire-grazing interaction has largely been in mesic (> 600 mm annual precipitation) grasslands and savannas worldwide (Fuhlendorf and Engle, 2004; Murphy and Bowman, 2007; Sensenig et al., 2010). In semiarid grasslands, where vegetation productivity is reduced due to precipitation, the strength and effects of the fire-grazing interaction may be reduced or lessened. Herbivore preference for burned areas and subsequent vegetative response in the shortgrass prairie is reduced to half of what occurs in the tallgrass prairie (Augustine and Derner, 2014). The feedbacks and responses of the interaction can be difficult to predict in semiarid grasslands where there is large variability in precipitation (Knapp and Smith, 2001). Topoedaphic variability across a landscape also influences vegetation composition, productivity, and structure (Davies et al., 2007; Dodd et al., 2002; Reed et al., 2009), constraining the response of vegetation to fire (Benning and Seastedt, 1995) and the subsequent grazing preferences of herbivores (Bailey et al., 1996; Winter et al., 2011).

Patch burn grazing is a management strategy that employs the fire-grazing interaction to mimic historical disturbances and processes, and to create landscape heterogeneity (Ricketts and Sandercock, 2016). Fire is applied to spatially distinct sections of a management unit (hereafter referred to as a patch) through time. Cattle prefer recent burned areas and concentrate grazing therein while avoiding or not selecting other areas with greater time since fire. This continuum from recent burned/grazed to unburned/ungrazed results in a shifting mosaic with defined vegetation contrasts (Fuhlendorf and Engle, 2001). As a result, landscape heterogeneity is increased, improving both the quality and quantity of habitat for a diversity of wildlife species (Fuhlendorf et al., 2006; Gregory et al., 2010; Holcomb et al., 2014). Furthermore, patch burn grazing maintains cattle weight gains at neutral to positive levels with improved stability through time (Allred et al., 2014; Augustine and Derner, 2014; Fuhlendorf and Engle, 2004; Limb et al., 2011).

As grasslands across North America have declined to less than 20% of their historic area (Knopf, 1994; Noss et al., 1995) the Northern Great Plains is one of the last remaining, large intact mixed grass prairies in North America (Cooper et al., 2001). Land ownership is a mix of public, private, and tribal. 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 (Allred et al., 2015; Fargione et al., 2012). 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). Additionally, increasing homogenization of vegetation structure continues to occur in remaining native prairie as a result of human alterations to historical fire and grazing regimes (Askins et al., 2007; Derner et al., 2009). Alternative management strategies are needed 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 (Strong et al., 2013; Vermeire et al., 2011; Whisenant and Uresk, 1989) resilient to both fire and grazing (Gates et al., 2017; Vermeire et al., 2014). Our goal was to examine the strength of fire-grazing interaction in the Northern Great Plains. We do not compare the fire-grazing interaction with other management strategies, but rather directly examine 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) forage quantity and quality; and 3) vegetation structure and composition.

Methods

Study Site

We examined the fire-grazing interaction at The Nature Conservancy (TNC) 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 (*Elymus-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 comprised 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 was 251 mm at 92% of the 30 year average in 2015 and 480 mm at 176% in 2016 (Fig. 1; PRISIM, 2017).

Study Design

Rotational grazing was used at moderate stock densities for two to three weeks (Table 1). Pasture A was grazed from June 2 - 17 and May 16 - June 11 in 2015 and 2016, respectively; pasture B was grazed from June 8 - July 1 and May 16 - June 11 in 2015 and 2016, respectively. Prescribed fire was conducted in early April when vegetation was dormant and prior to spring precipitation (Fig. 2). Different sections of pasture A were burned consecutively from 2014 through 2016. Due to unfavorable weather conditions pasture B was burned only in 2015, reducing our sample size. Though moderate fuel loads were present, burns were often patchy in nature due to topography and disruptions in fuel continuity. These pastures had not been burned for at least 20 years prior to this study.

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 hours apart for independence) from 6:00 am through 9:00 pm each day (3-5 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 (Schuler et al., 2006; Vinton et al., 1993). 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 to other studies. Patch 4 was excluded, as it comprised only 10% of pasture area and was not comparable to other studies. We also quantified cattle use by counting fresh cattle dung pats along twelve (45 x 4 m) belt transects in each patch (Archibald et al., 2005; Barnes, 2001). Dung pats were identified as fresh by containing increased moisture and decreased viscosity than pats deposited during previous years. 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 in grazing exclosures and paired grazed sites in four different locations per patch. Biomass samples were oven dried at 50° C for 72 hours and weighed;

utilization was calculated as the difference in biomass from within and outside of exclosures.

Forage Quantity and Quality

We harvested aboveground standing biomass (live and dead) using a 0.25 m^2 frame from 15 different locations per patch from May - August during 10 sampling periods in 2015 and 11 in 2016. Sampling occurred weekly during cattle grazing and then biweekly thereafter. Biomass samples were oven dried at 50° C for 72 hours and weighed. Three biomass samples per patch were analyzed for crude protein (%) at biweekly intervals from 7 sampling periods in 2015 and 8 in 2015. 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.

Cattle Grazing Selection for Graminoid Species

Grazing selection for graminoid species was determined during vegetation data collection using the same transects. Along each transect the number of grass clumps (minimum basal width of 0.5 cm) intersecting the 20 m transect were recorded for each grass species present. Clumps were recorded as grazed if grass stems had been clipped by cattle during grazing of the current year. The percent of plants grazed was calculated for each species by dividing the number of grazed clumps by the total number of clumps along transects.

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 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 and grazed graminoid species at the patch level with the DECORANA function in the R package VEGAN (Oksanen et al., 2016). Sampling locations (transect/patch) were arranged in DCA based on variation in species composition and abundance, reflecting overall environmental variation. The influence of individual variables on the total ecological variation expressed across species or sampling locations 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 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 recent burned patches along the gradient of time since fire across the suite of selection metrics. Cattle grazed recent 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 recent burned patches to 0.7 in unburned patches. SI values in recent burned patches were consistently > 1 during both years, indicating strong patch preference. Selection preferences varied between years; in 2015 preference for recent burned patches increased with week of year, while in 2016 it decreased. Preference for patches at one year since fire and unburned were lower in 2015 than in 2016 corresponding with higher selection occurring in recently burned patches. During 2016, SI values were the lowest across patches in the single patch at two years since fire. Time since fire (weeks) of a patch and SI had a significant negative relationship across both years (Fig. 3B, $p < 0.01$). Counts of fresh cattle dung pats significantly decreased as years since fire of a patch increased (Fig. 4A, $F_{2,6} = 29.76$, $p < 0.01$, ANOVA). Dung pats in the patch at two years since fire followed the declining trend with greater time since fire, but was excluded from the analysis since a single replicate. Cattle grazing utilization also significantly decreased with greater time since fire (Fig. 4B, $F_{2,6} = 7.18$, $p < 0.05$, ANOVA). Utilization in recent burned patches was significantly greater than unburned patches ($p < 0.05$, Tukey HSD). Unburned patches received greater utilization than the single patch at two years since fire, which had no utilization (value of 0) and was excluded from analysis as a single replicate.

Forage Quantity and Quality

Forage quantity varied with time since fire and day of year (doy) (Fig. 5A). Biomass was the lowest in recent burned patches, though large fluctuations occurred across the growing season. In patches at one year since fire biomass stayed above recent burned patches and by the end of sampling was almost the same as at two years since fire. 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 unburned patches following grazing (doy 180). At the end of sampling for each year, biomass was similar in patches at one year since fire and recent burned, though still below unburned 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 recent burned patches. The patch at two years since fire contained similar levels of biomass as unburned patches throughout 2016. Biomass in burned patches had a significant positive relationship with days since fire (Fig. 5B, $p < 0.01$).

Forage quality in recent burned patches was nearly twice as high as other patches at the start of the growing season and was also increased to a lesser degree in patches at one year since fire (Fig. 6A). However, by the end of the growing season 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 protein occurred in 2016 for all patches with substantially higher levels in recent burned patches. No noticeable changes in protein occurred following grazing in 2015, though it increased slightly across patches following grazing (doy 180) in 2016. Protein in recent burned patches had a significant negative relationship with days since fire (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. Site scores on DCA axis 1 were significantly influenced by years since fire, though weakly correlated (Fig. 7B, $p < 0.01$, r^2 =33%). Site scores on axis 1 were strongly correlated and significantly influenced by patch location ($p < 0.01$, r^2 =57%). There was no clear correlation for site scores on axis 2 with environmental variables or time since fire.

Cattle Grazing Selection for Graminoid Species

The two axes of the DCA accounted for 23% of the variance in cattle grazing selection for graminoid species in patches varying in time since fire. On DCA axis 1 the order of primary influence by species was: prairie junegrass (*K. macrantha*), Japanese brome (*B. japonicas*), green needlegrass (*N. viridula*), and needle-and-thread (*H. comata*) (Fig. 8A). For DCA axis 2 the order was: Japanese brome (*B. japonicas*), crested wheatgrass (*A. cristatum*), threadleaf sedge (*C. filifolia*), and needle-and-thread (*H. comata*). Site scores on DCA axis 1 were only correlated with year (Fig. 8B, r^2 =59%, $p < 0.01$) and on DCA axis 2 were only correlated with patch (r^2 =78%, $p < 0.01$).

Discussion

The ecological interaction between fire and grazing is clearly present in the Northern Great Plains; however, this interaction is weaker than in mesic grasslands as productivity is decreased and tightly regulated by topoedpahic variability. Feedbacks between time since fire and cattle grazing selection are coupled and consistent in the Northern Great Plains, primarily driven by responses in forage quality. Cattle preferentially grazed recent burned patches over others with greater time since fire, as demonstrated in mesic grasslands (Allred et al., 2011). Forage quantity did not appear to be a mechanism of selection as cattle consistently grazed recent 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 forage quality regardless of reductions in quantity, as demonstrated in grasslands worldwide (Eby et al., 2014; Murphy and Bowman, 2007; Sensenig et al., 2010).

The strength of cattle preferences for recent burned patches in the Northern Great Plains fits between sites at the productivity extremes of the Great Plains. In the shortgrass prairie cattle grazed recent burned patches comprising a quarter of pasture area 31% of the time (Augustine and Derner, 2014), while in the tallgrass prairie cattle grazed recent burned patches comprising a third of pasture area 75% of the time (Fuhlendorf and Engle, 2004). Cattle selection for recent burned patches in the Northern Great Plains was in between tallgrass and shortgrass prairies, as cattle grazed recent burned patches comprising approximately a quarter of pasture area 48% of the time. A comparison of selectivity indices (SI)–which accounts for variability in patch size–between tallgrass and mixed grass prairies similarly indicates stronger selection for burned areas in the Southern Great Plains (Schuler et al., 2006; Vinton et al., 1993).

The primary driver creating differences in cattle grazing selection across the Great Plains is the magnitude of increase in protein in recent burned patches compared to unburned patches as influenced by variability in precipitation. Both cattle burn preference (75%) and protein increase (450%) in the tallgrass prairie (Allred et al., 2011) are roughly 2.3 fold greater than cattle burn preference (31%) and protein increase (200%) in the shortgrass prairie (Augustine and Derner, 2014; Augustine and Milchunas, 2009). 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. 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. The gradient in cattle grazing selection closely corresponds with the gradient in protein response to fire across the Great Plains. These comparisons demonstrate that the persistence of feedbacks between fire and grazing selection are likely driven by differences in protein as influenced by vegetation production and climatic variation.

Both cattle use and grazing utilization indicate that cumulative patch use is similarly increased in recent burned patches, as shown at shorter observational periods with cattle preferences calculated with the SI. Cattle use quantified by dung counts was nearly three fold higher in recent burned patches compared to unburned patches and declined with greater time since fire. Patch use in recent burned patches, however, was reduced compared to mesic grasslands where dung counts are increased four to six fold (Archibald et al., 2005; Sensenig et al., 2010). Grazing utilization followed a weaker gradient than dung counts with significant differences only between recent burned and unburned patches. Grazing utilization for the patch at two years since fire did not follow the gradient of time since fire as it was below unburned patches with a value of zero. This single patch was likely avoided by cattle during 2016 (Fig. 3) as it had the lowest protein levels across patches (Fig. 6). 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 one year since fire throughout the study. This created an opportunity to examine cattle selection for a single burn patch in a pasture compared to the other pasture containing a mosaic of burn patches. In 2015 all three metrics of cattle selection in recent burned patches did not vary between pastures. However, in 2016 cattle exhibited stronger selection along all three metrics for patches at one year since fire in pasture B, demonstrating that cattle strongly select burn patches even after one year since fire within a broader unburned landscape.

Variation in cattle grazing selection for different graminoid species was primarily explained by year and patch location. Year strongly influenced variance on DCA axis 1, reflecting changes in grass species abundance with fluctuations in annual precipitation.

Prairie junegrass (*K. macrantha*) and Japanese brome (*B. japonicas)* had the greatest variance on this axis, which is not surprising as Japanese brome is an annual species with abundance changing with precipitation (Whisenant, 1990). However, variation in cattle species selection was also explained by patch on DCA axis 2 where Japanese brome (*B. japonicas)* and crested wheatgrass (*A. cristatum*) had the greatest variability. The occurrence of both species and their preference by cattle varied with patch location as influenced by burn history and topoedaphic factors. Both Japanese brome and crested wheatgrass are introduced species and common across the Northern Great Plains with abundance fluctuating with burning and grazing (Gates et al., 2017; Harmoney, 2007; Lodge, 1960). Though time since fire was not strongly correlated with the variation in grazed graminoids across transects, the DCA does indicate a slight gradient produced across time since fire from left to right (Fig. 8B). The fire-grazing interaction likely encouraged consumption of grasses that are often avoided as fire removes cured stems and litter that normally deter herbivory (Ganskopp et al., 1993). In addition, the scale of grazing selection in recent burned patches likely shifted from the species level to the patch level (Archibald and Bond, 2004; Fuhlendorf and Engle, 2004), resulting in the utilization of plants that are normally avoided (Coppedge and Shaw, 1998; Helzer and Steuter, 2005). The fire-grazing interaction increases utilization of typically avoided and invasive plants in the tallgrass prairie, decreasing invasion rate three fold (Cummings et al., 2007; Fuhlendorf and Engle, 2004). The fire-grazing interaction may similarly be an effective treatment to increase grazing selection for invasive plant species in the Northern Great Plains.

Reduced variance in harvested biomass occurred in recent burned patches, likely as a result of shifted grazing selection from particular species to the patch as indicated by cattle graminoid selection. Vegetation heterogeneity is similarly reduced within recent 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). However, 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.

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 large increases in productivity during the first growing season post fire with growth substantially declining in subsequent growing seasons. In a year with average precipitation low biomass in recent 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). Biomass in the mixed grass prairie can increase by 450% due to precipitation regardless of fire and grazing (Vermeire et al., 2014). Precipitation immediately following and in subsequent years after fire similarly constrains the response of plant production in the shortgrass prairie (Bennet et al., 2003). Levels of biomass production were similar to other semiarid regions postfire (50-160 g m^{-2}), though reduced compared to the tallgrass prairie (100-900 g m^{-2}) (Allred et al., 2011; Augustine and Derner, 2014). Biomass production returned to unburned levels within two to three years, indicating resilience to both fire and grazing.

Increased protein occurred in recent burned patches as a result of vegetation regrowth containing young tissues high in nitrogen (Eby et al., 2014; Sensenig et al., 2010; Van deVijver et al., 1999). The strong negative log relationship between days since fire and crude protein demonstrates that enhanced protein in recent burned patches occurs for only a short timeframe in the first half of the growing season before declining as biomass increases. Forage quality declines with tissue maturation as the growing season progresses (McNaughton, 1985), however, the fire-grazing interaction slows down the rate of decline in recent burned patches compared to other patches with greater time since fire. Higher protein in 2016 probably occurred in response to precipitation increasing growth rates, as indicated by biomass. In addition, both nitrification and plant N uptake show short term increases in response to pulses of precipitation in semiarid grasslands (Dijkstra et al., 2012). Enhanced forage quality in recent burned patches during the early growing season was maintained above 10% protein halfway through the growing season. Increased protein in recent burned patches and subsequent focal grazing are essential for the productivity of both cattle and wildlife around the globe (Parrini and Owen-smith, 2009). Cattle weight gains are similar or improved with patch burn grazing compared to traditional management in the semiarid shortgrass prairie (Augustine and Derner, 2014; Augustine and Milchunas, 2009). Cattle weight gain in the mixed grass prairie may be similarly equal to greater, especially given the increased response of protein to fire in the mixed grass prairie (350%) compared to the shortgrass prairie (200%) (Augustine and Milchunas, 2009).

Similar to other semiarid regions, the fire-grazing interaction had little influence on plant species composition (Gates et al., 2017; Vermeire et al., 2014), demonstrating resilience to fire and grazing. Relatively similar site scores in the DCA indicate close ecological distances between plant functional groups. However, a gradient was present on the DCA plot (Fig.7B) with unburned 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 an unburned state with reduced grazing utilization. Functional groups related to soil 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 soil surface is impacted by disturbance. Soil and bare ground increased with increasing time since fire as plant canopy cover increased. Club-moss, however, decreased with increasing time since fire as increasing plant cover likely decreased sunlight availability. Variation on DCA axis 2 was weakly explained by the full gradient of time since fire as variability due to the fire-grazing interaction is only detectable during the immediate growing season post fire as the mixed grass prairie is highly resilient to disturbance (Gates et al., 2017). Large variability occurred with litter and bare ground across sites on DCA axis 2. Litter and bare ground are related to plant biomass, which quickly increased following the fire-grazing interaction in recently burned patches. Variation across transects was also likely a result of prescribed fires and grazing producing a mosaic of areas with high to low consumption and resulting influence on amount of litter and ground cover.

Management Implications

Only 20% of the once extensive grasslands across North America remain (Noss et al., 1995; Samson and Knopf, 1994) 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 (Lipsey and Naugle, 2016; Lwiwski et al., 2015). 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 distinct 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 (Kunkle et al., 2013; Millett and Johnson, 2009), 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 unburned levels after two years since 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 noticeable change in cattle grazing behavior 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 (Augustine and Derner, 2015; Bailey, 2004). Enhanced forage quality in recent 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 quality in the months following fire, plant communities are still primarily regulated by climate and topoedaphic factors.

Tables

Table 1. Fire-grazing interaction study design for two pastures in the Northern Great Plains for years 2015 and 2016. Pasture letters and patch numbers correspond with those in Figure 2.

Pasture area (ha)	Stock rates (AUM ha^{-1})	Year	Years since fire	Burn size (ha), % pasture area	Patch
A: 355	1.05	2015	1	70 (20%)	1
			0	145 (41%)	2
	1.16	2016	2	70 (20%)	1
			1	145 (41%)	2
			0	73 (21%)	3
B: 533	0.62	2015	0	55 (10%)	4
	0.68	2016	1	55 (10%)	4

Figures

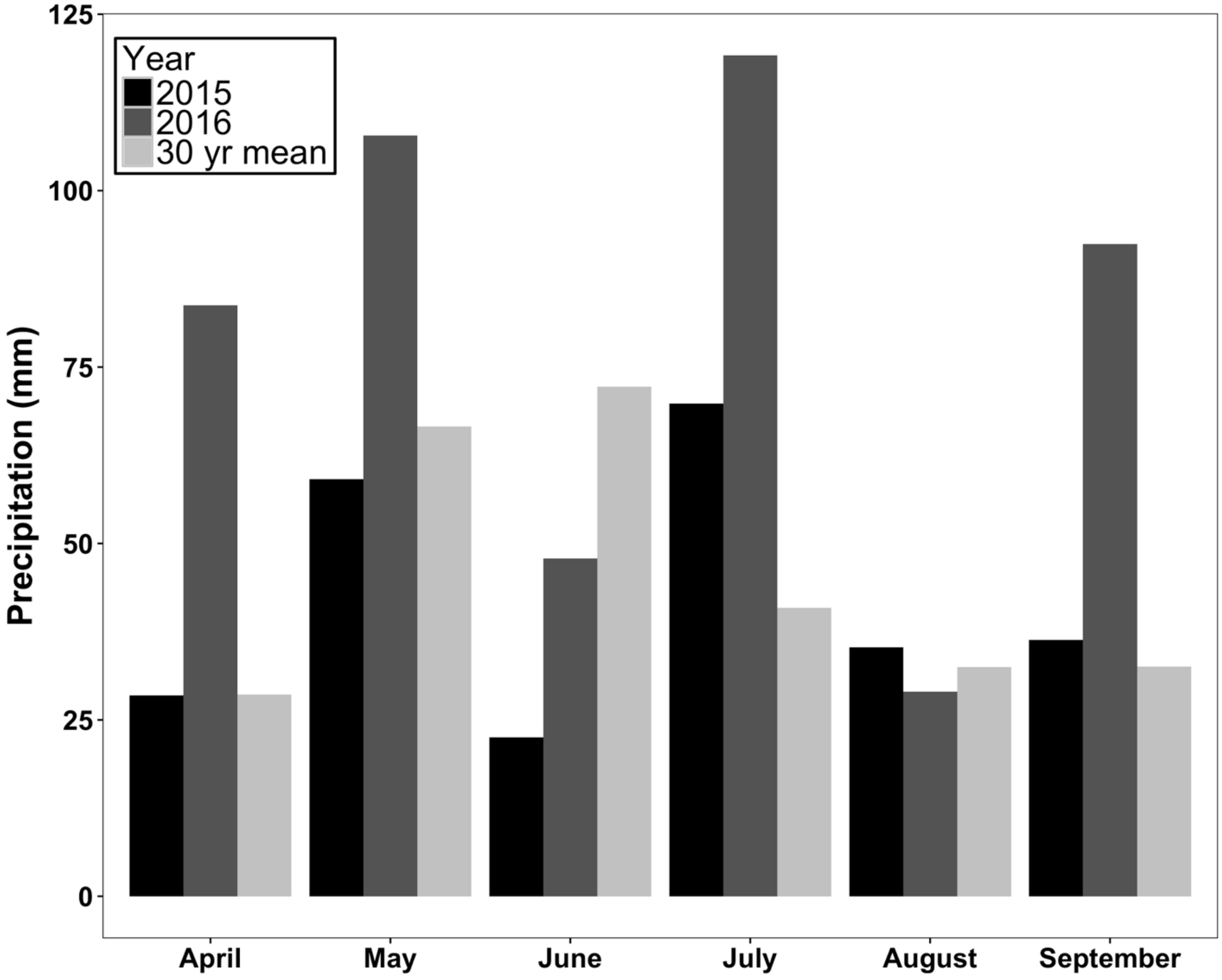

Figure 1. Total monthly precipitation during the growing season (April-September) at The Nature Conservancy Matador Ranch in northeast Montana during 2015, 2016, and 30 year average (PRISM Climate Group).

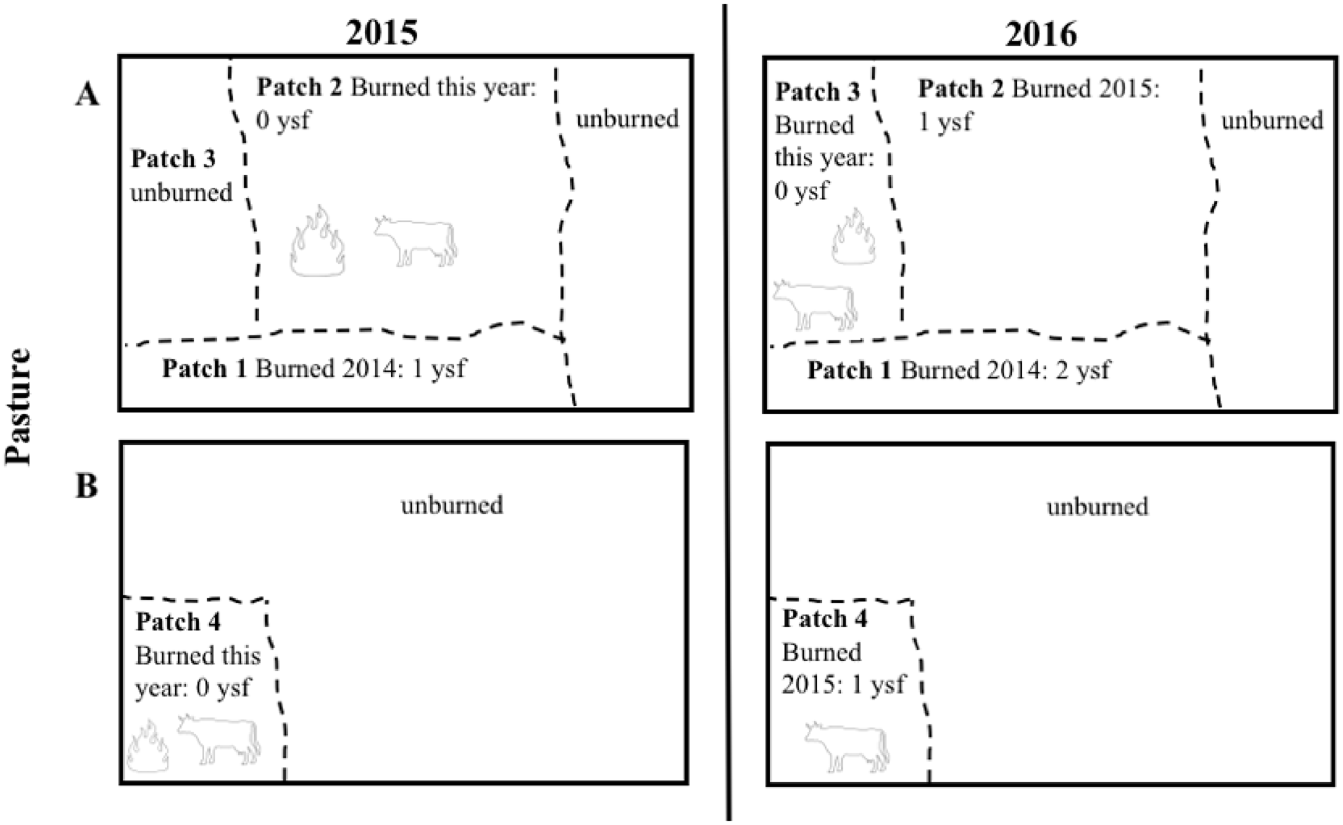

Figure 2. Fire-grazing interaction study design in the Northern Great Plains for years 2015 and 2016. Pasture A and B, along with patch numbers correspond with those in Table 1. Solid lines indicate pasture fence boundaries; dotted lines indicate patch location of fires. Years since fire (ysf) of patches 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.

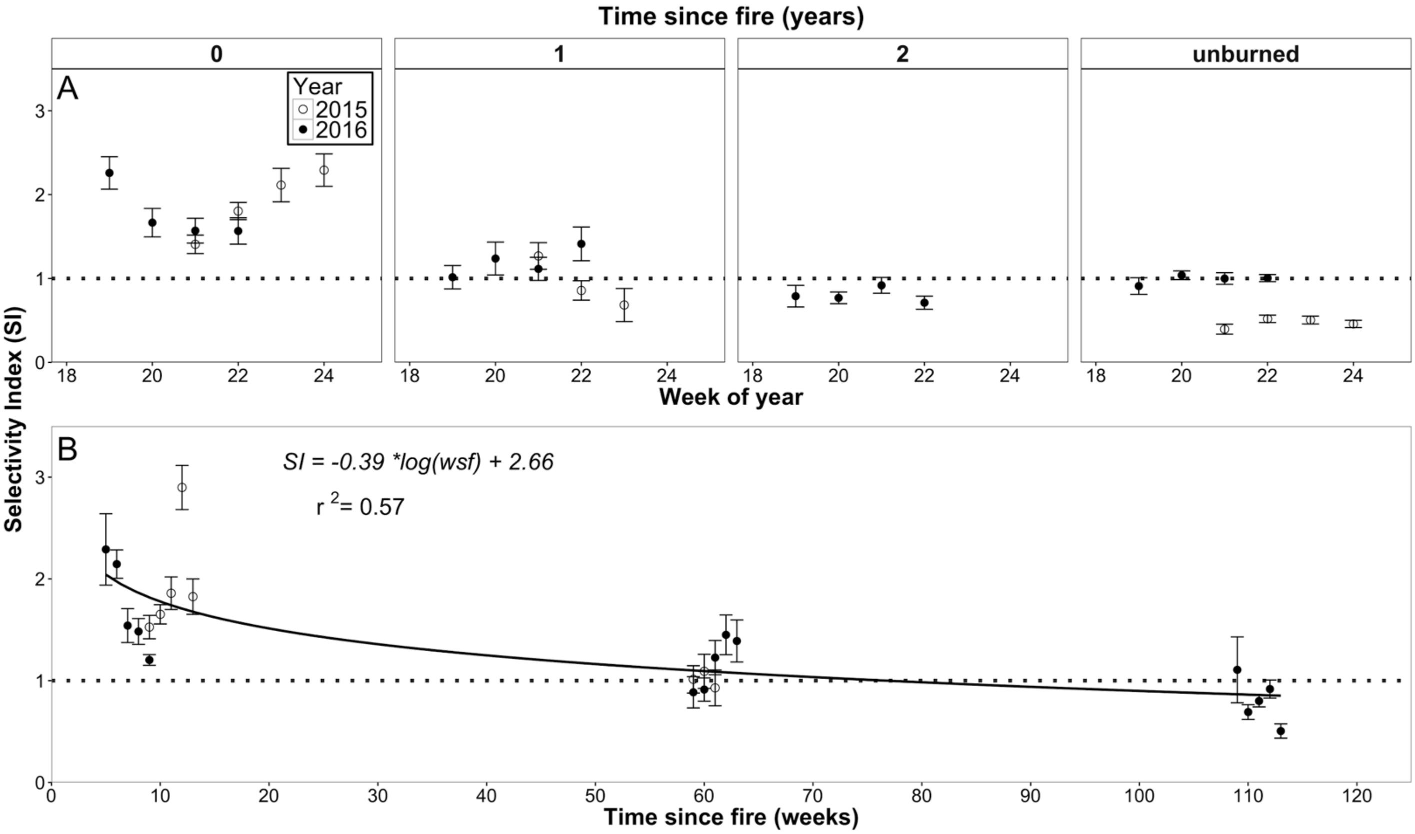

Figure 3. (A) Cattle grazing preferences for unburned and burned patches during 2015 and 2016 in the Northern Great Plains plotted by week of year; grazing preferences expressed as a selectivity index (SI). Points represent weekly averages from multiple daily observations. Dotted line indicates preference 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.

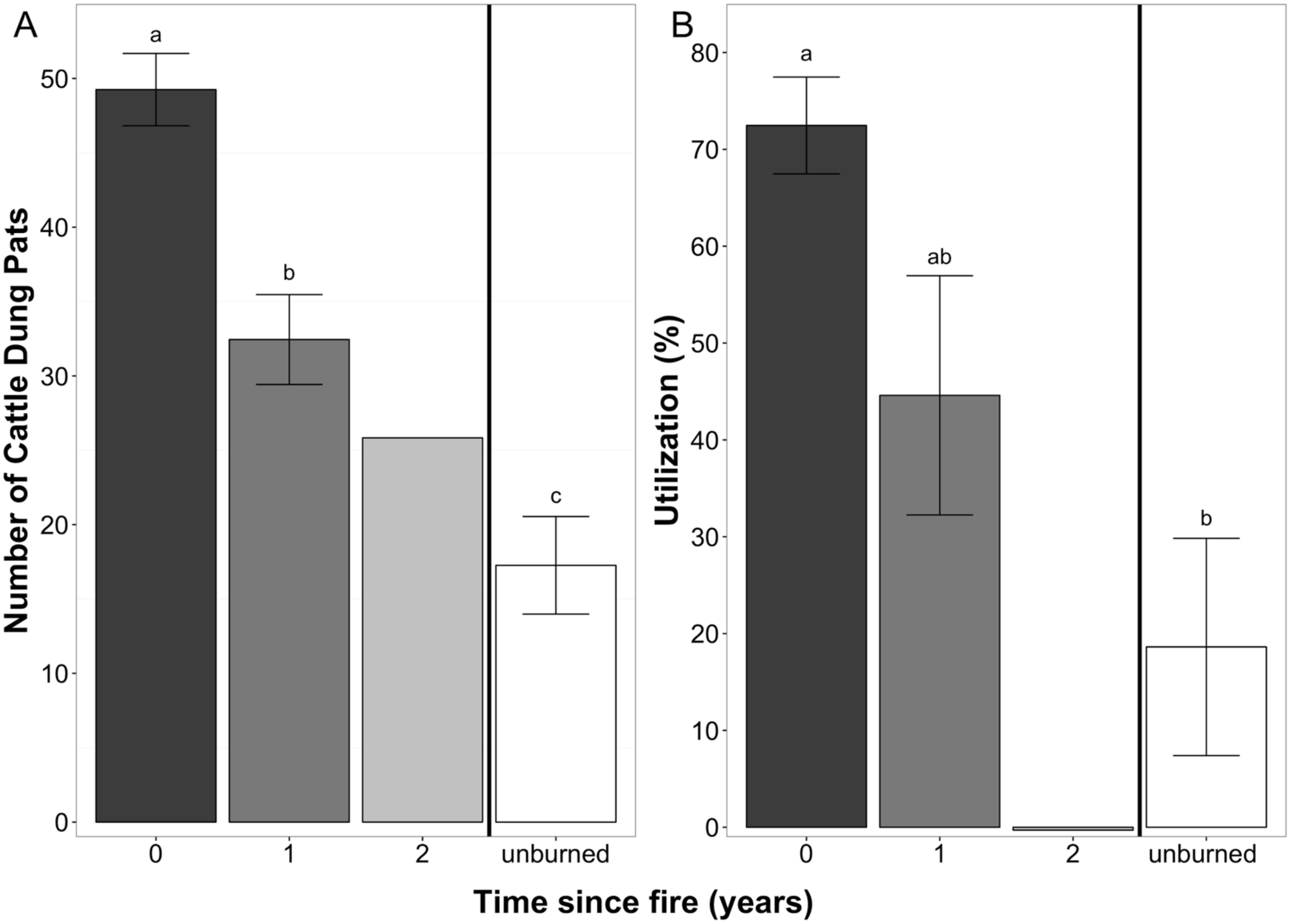

Figure 4. (A) Number of fresh cattle dung pats counted in patches relative to time since fire in the Northern Great Plains. Bars with different letters above them indicate significant differences ($p < 0.05$, Tukey HSD). Error bars represent one standard error. (B) Grazing utilization (%) for patches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

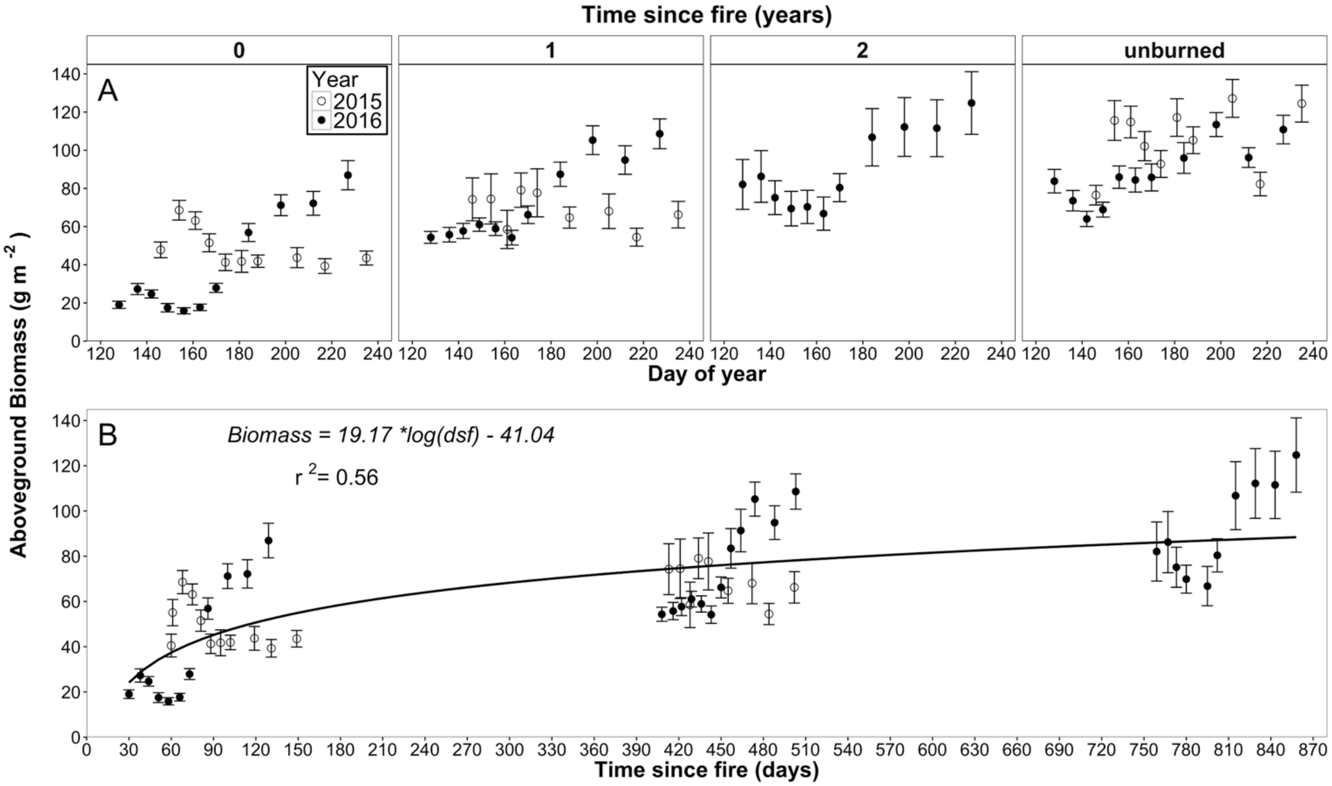

Figure 5. (A) Aboveground biomass (g m^{-2}) by day of year through the growing season (May-August) in burned patches varying in time since fire (years) in the Northern Great Plains. (B) Aboveground biomass by time since fire (days) of burned patches across the study period. Aboveground biomass sampled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

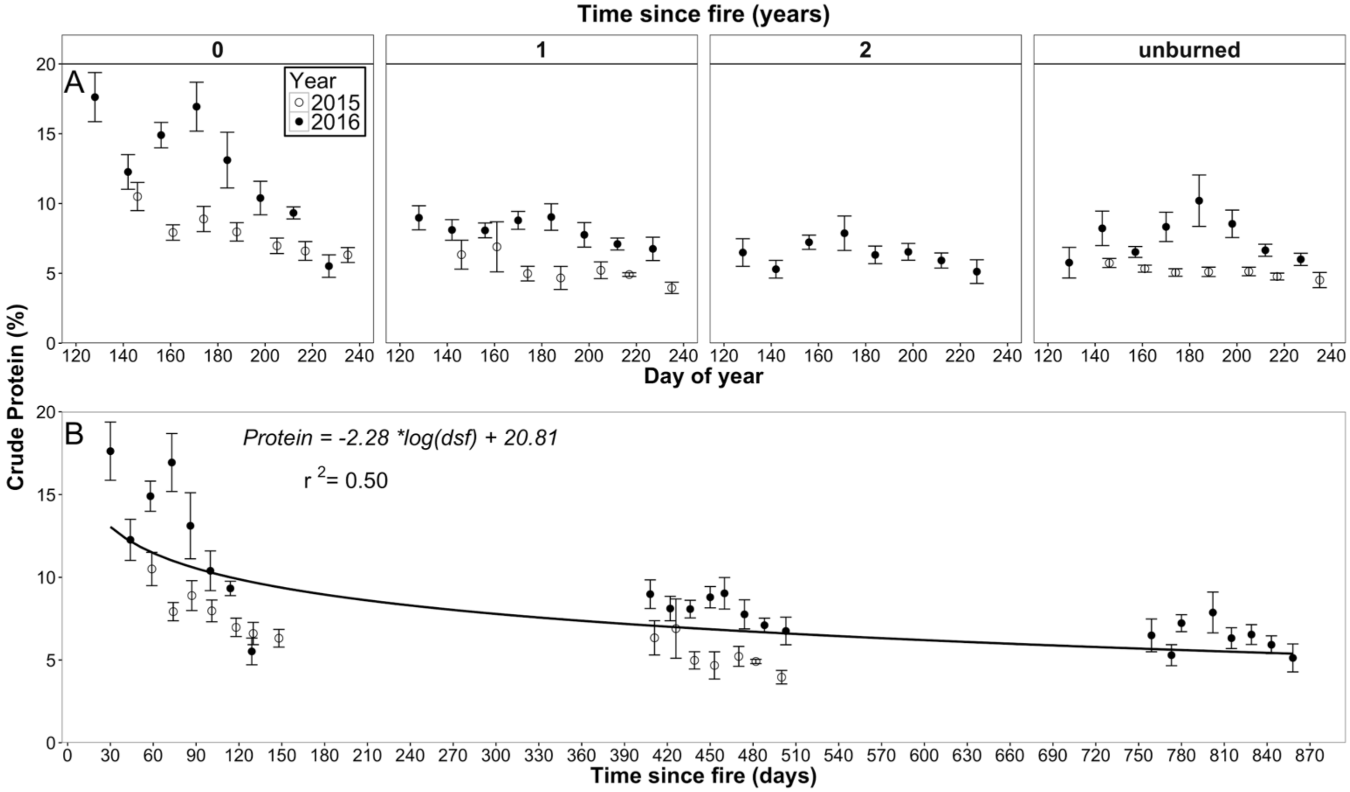

Figure 6. (A) Crude protein (%) of biweekly harvested standing biomass by day of year across the growing season (May-August) in burned and unburned patches varying in time since fire (years) in the Northern Great Plains. (B) Crude protein (%) by time since fire (days) of burned patches across the study 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.

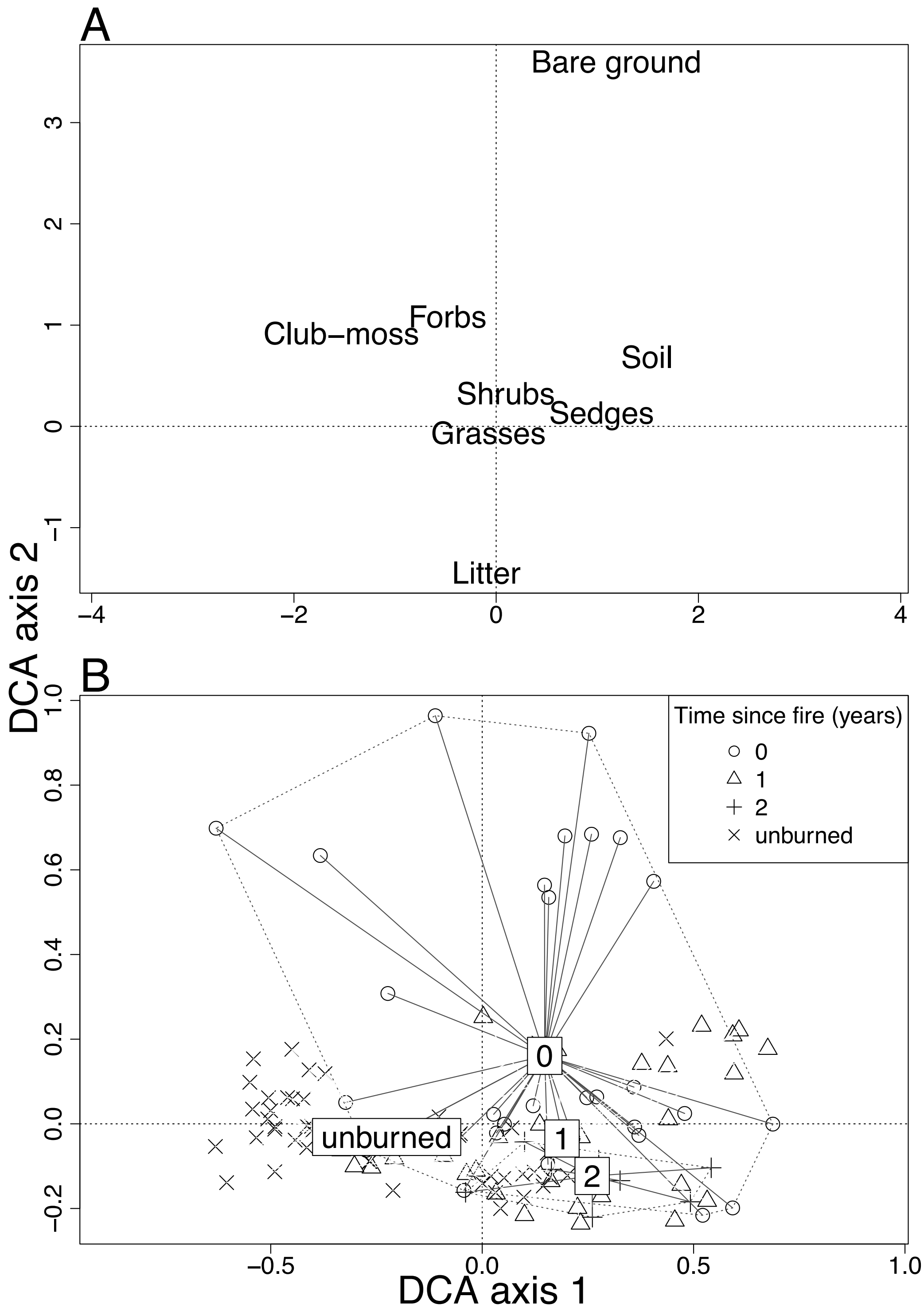

Figure 7. Plots of the first two axes of the detrended correspondence analysis for vegetation structure in burned and unburned patches varying in time since fire (years) in the Northern Great Plains. (A) Species scores for plant functional groups, along with litter and bare ground; (B) Site scores for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

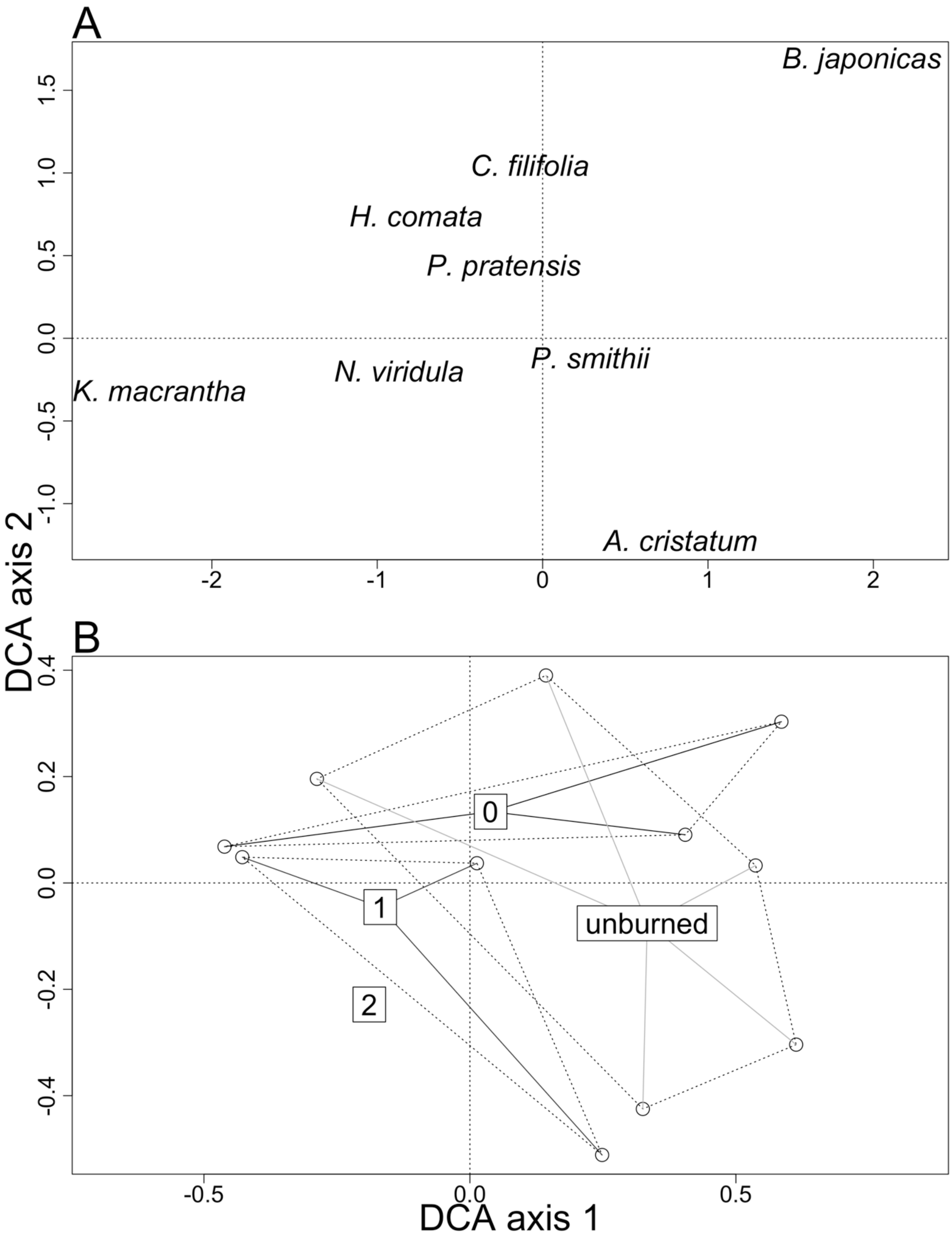

Figure 8. Plots of the first two axes of the detrended correspondence analysis for grazed graminoid species in burned and unburned patches varying in time since fire (years) in the Northern Great Plains. (A) Species scores for grass species; (B) Site scores for unburned and burned patches varying in time since fire (years), spindles connecting sites and envelopes around sites indicate time since fire (years).

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Improving grazing selection and control of *Agropyron cristatum* with patch burn grazing and herbicide

Introduction

Several deliberate and accidental introductions of exotic forage species have occurred across rangelands (D'Antonio and Vitousek, 1992; Williams and Baruch, 2000). Introduced perennial grasses are frequently planted as forage species across semiarid rangelands for their quick establishment and high production (Lawrence and Ratzlaff, 1989). Control of introduced species with these intentionally selected traits is difficult given their prolific seed production, multiple modes of reproduction (seed or vegetative), and grazing deterrence mechanisms (high stem-to-leaf ratio, high lignin) (Barnes et al., 2003). These resilient traits allow for the continued establishment and spread of exotic forage species, often in an unpalatable state avoided by herbivores (Brandon et al., 2004).

Crested wheatgrass (*Agropyron cristatum* [L.] Gaertner) is an introduced cool season perennial caespitose grass that has been widely planted across the western United States to reduce erosion and persist through harsh grazing and drought conditions (DeLuca and Lesica, 1996; Henderson and Naeth, 2005). Since the 1930s, 6 to 11 million ha of the Great Plains have been seeded with crested wheatgrass (Rogler and Lorenz, 1983; Vaness and Wilson, 2008). Crested wheatgrass is persistent in both native and introduced ranges with mortality limited to extreme drought conditions (Mclean and Van Ryswykr, 1973). This persistent exotic grass also produces a large seed bank with viability lasting for five years (Hulet et al., 2010; Marlette and Anderson, 1986) and spreads from vegetative tillers in response to defoliation or drought stress (Cook and Stoddart, 1953; Romo and Harrison, 1999). Crested wheatgrass is valuable early spring forage for livestock as it initiates growth two weeks prior to native cool season grasses (Holecheck et al., 2004). However, cattle preference declines later in the growing season when numerous stems and culms senesce earlier than native species (Hyder and Sneva, 1963).

While crested wheatgrass can be valuable forage for livestock it also has several negative impacts on grassland ecosystems. The grass is capable of displacing native plant species, most commonly by spreading downwind of planted monocultures into native rangeland over several years (Grant-hoffman et al., 2012; Heidinga and Wilson, 2002). Crested wheatgrass has multiple impacts on nutrient cycling by increasing bare ground (Sutter and Brigham, 1998), reducing available soil nitrogen and carbon (Christian and Wilson, 1999), and decreasing phosphorus and soil organic matter (DeLuca and Lesica, 1996). Native plant diversity and growth rates of native shrubs and grasses are reduced by crested wheatgrass (Gunnell et al., 2010). Rangelands with crested wheatgrass also contain lower densities of reptiles, birds, and mammals than native rangelands (Reynolds and Trost, 1980). Bird species of conservation concern, such as the Chestnut-collared Longspur (*Calcarius ornatus*), have lower nest survival and growth rates in habitats with crested wheatgrass (Lloyd and Martin, 2005).

Crested wheatgrass presents a challenge in the Northern Great Plains since it creates ecological concerns, while at the same time remaining an important and often underutilized forage for livestock. The Northern Great Plains is one of the last remaining, large intact mixed grass prairies in North America (Cooper et al., 2001). However, crested wheatgrass was widely planted in the Northern Great Plains during the 1930s on abandoned homesteads (Rogler and Lorenz, 1983) and after 1985 on idle cropland lands enrolled in USDA’s Conservation Reserve Program (CRP) (DeLuca and Lesica, 1996). Other threats to grassland conservation and sustainability in the Northern Great Plains include continued agricultural conversion (Lark et al., 2015) and energy development (Allred et al., 2015; Fargione et al., 2012). Given the increasing pressure on grasslands and amount of crested wheatgrass in the Northern Great Plains, an optimal solution is needed to control crested wheatgrass that has invaded otherwise intact, native grasslands or where restoration to native vegetation is desired, while supporting sustainable ranching.

Previous research on controlling crested wheatgrass in the Northern Great Plains has examined clipping, herbicide, seeding native grasses, and tilling (Bakker et al., 1997; Hansen and Wilson, 2006; Wilson and Gerry, 1995; Wilson and Partel, 2003). Long term control is difficult due to tiller growth in surviving plants and a large seed bank (Bakker et al., 2003; Pyke, 1990; Romo and Harrison, 1999; Vaness and Wilson, 2008). Nonselective glyphosate herbicide applied annually over four to seven years only reduces cover and does not eradicate crested wheatgrass (Bakker et al., 1997; Wilson and Partel, 2003). The effectiveness of herbicide varies with the time of application and plant phenology, while simulated grazing through experimental clipping maintains low plant cover through time (Hansen and Wilson, 2006; Wilson and Partel, 2003). However, in order for grazing to be an effective treatment a mechanism is needed to overcome the low palatability of crested wheatgrass, which is often avoided by cattle when it has not been defoliated, due to its high stem-to-leaf ratio and early senescence compared to native grasses (Hyder and Sneva, 1963). Patch burn grazing might increase grazing by removing litter (Augustine and Milchunas, 2009; Vermeire et al., 2014) and improving palatability

(Engle and Bultsma, 1984; Engle et al., 1990; Vermeire et al., 2011). Patch burn grazing is a management strategy 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 a patch) through time. Cattle concentrate grazing in the most recent burned patch and shift grazing selection from the species level to the patch level (Archibald and Bond, 2004; Fuhlendorf and Engle, 2004), resulting in the utilization of plants that are normally avoided (Coppedge and Shaw, 1998; Helzer and Steuter, 2005). In the tallgrass prairie patch burn grazing overrides grazing deterrence mechanisms (high tannins) of an exotic forb, sericea lespedeza (*Lespedeza cuneata*), stabilizing plant cover and decreasing the rate of spread by three fold compared to traditional management (Cummings et al., 2007; Fuhlendorf and Engle, 2004). In the shortgrass steppe patch burn grazing similarly increases grazing of plains pricklypear (*Opuntia polyacantha*) by five fold in recently burned patches (Augustine and Derner, 2015). We believe that cover of crested wheatgrass will be similarly reduced in recent burned patches in the Northern Great Plains.

Patch burn grazing may be an optimal solution to manage crested wheatgrass as it gives ranchers the opportunity to graze the available forage base, while potentially reducing its negative impacts on wildlife and ecosystem functioning. Combining patch burn grazing with herbicide application may further enhance control of crested wheatgrass as fire and grazing will remove accumulations of litter that reduce herbicide coverage on live plant stems (DiTomaso et al., 2006; Enloe et al., 2013; Seymour et al., 2008). Previous research in the Northern Great Plains has examined the use of burning to control exotic species, but the use of patch burn grazing to control invasive plant species is a novel strategy for the region. Our objective was to determine the influence of time since fire, within the context of patch burn grazing, on crested wheatgrass cover and glyphosate herbicide efficacy.

Material and Methods

Study Site

We examined patch burn grazing at The Nature Conservancy (TNC) 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 on ridges and clayey loams in lowlands. 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 (*Elymus-Hesperostipa*) communities, along with interspersed forbs and subshrubs. Common forbs are common yarrow (*Achillea millefolium* L.) and hairy false goldenaster (*Heterotheca villosa* [Pursh] Shinners). Shrubs are comprised of prairie sagewort (*Artemisia frigida* Willd.) and silver sagebrush (*Artemisia cana* Pursh.). Graminoids include needle and thread (Hesperostipa comata [Trin. & Rupr.] Barkworth), blue grama (*Bouteloua gracilis* [Willd. ex Kunth.] Lag. ex Griffiths), green needlegrass (*Nassella viridula* [Trin.] Barkworth), and western wheatgrass (*Pascopyrum smithii* [Rydb.] A. Löve). Introduced grasses include crested wheatgrass (*Agropyron cristatum* [L.] Gaertner), Japanese brome (*Bromus japonicas* Thunb.), and Kentucky bluegrass (*Poa pratensis* L.). Growing season precipitation (April-September) in 2016 was 480 mm at

176% of the 30 year average. Annual precipitation was 348 mm in 2015 (97% of average) and 670 mm in 2016 (187%) (PRISIM, 2017).

Patch Burn Grazing Design

We performed this study in a 355 ha pasture managed with patch burn grazing (Fig. 1). Prescribed fire was conducted annually from 2014 - 2016 in three different sections of the pasture, burn size varied from 70-145 ha (20 - 40% of total pasture area). Burning occurred in the early spring when vegetation was dormant and prior to spring precipitation. Though moderate fuel loads were present, burns were often patchy in nature due to topography and disruptions in fuel continuity. This pasture had not been burned for at least 20 years. Rotational grazing was used at a moderate stock density (1.16 AUM ha^{-1}) from May 16 - June 11 in 2016.

Plot Design

Fifteen paired 5 x 5 m plots with patch burn grazing were established in similar ecological sites across the pasture with five plots per burn patch. Paired plots were located adjacent to each other and exposed to patch burn grazing with one plot receiving herbicide, the second plot remaining unsprayed as a control. Plot locations were permanently marked with wooden stakes. Nonselective herbicide (2% Cornerstone Plus (41% active glyphosate ingredient), 1% blue die, and 0.25% Preference spray surfactant) was spot sprayed on crested wheatgrass in mid May of 2016 using a standard backpack sprayer.

Data Collection

The response of crested wheatgrass to patch burn grazing and herbicide was quantified by changes in aerial cover determined with a 0.25 x 0.5 m (0.125 m^2) Daubenmire frame (Bonham et al., 2004) in six different permanently marked quadrats per plot. Cover across treatments was initially measured in early May, one month after the patch was burned, but prior to grazing and herbicide application. Cover was again determined in all plots after herbicide and patch burn grazing in late June. In addition, herbicide efficacy on crested wheatgrass was quantified by plant mortality assessed at the larger plot level scale (25 m^2) to incorporate variability in plant survivorship. Plant mortality (%) was determined for crested wheatgrass by counting the number of individual dead plants out of the total number of plants across the plot.

Data Analysis

We analyzed cover changes using two-factor repeated measures ANOVA with time since fire and herbicide treatment as main factors, time since fire as a between groups factor and treatment as a within groups factor, along with the interaction between factors. Plot was treated as a random effect to account for site variability. Repeated measures ANOVAs were run separately for control plots testing only patch burn grazing and treatment plots testing both herbicide and patch burn grazing. A post hoc Tukey test was used for within treatment pairwise comparisons of cover pre and post treatment across patches varying in time since fire. Linear regression was used to test the relationship between crested wheatgrass mortality (%) and time since fire. All analyses were conducted using R (R Development Core Team, 2016).

Results

Patch Burn Grazing

Average cover of crested wheatgrass in control plots at initial sampling before patch burn grazing was the greatest in the recent burned patch, followed by two years since fire, and one year since fire (Fig. 2A). Cover of crested wheatgrass was significantly increased post patch burn grazing (Fig.2A, $F_{1,12} = 6.8$, $p < 0.05$, ANOVA). Patches at one year since fire showed the greatest change with significantly increased cover as the growing season progressed ($p < 0.01$, Tukey HSD). However, cover increased to a lesser degree in patches at two years since fire, and no change occurred in the recent burn. Average cover after patch burn grazing was the greatest at one year since fire, followed by two years since fire and the recent burn. There was no significant interaction between patch burn grazing and years since fire.

Herbicide with Patch Burn Grazing

Average cover of crested wheatgrass in treatment plots prior to herbicide and patch burn grazing was greater than control plots and similar across burns. Herbicide with patch burn grazing significantly reduced crested wheatgrass cover regardless of years since fire (Fig.2B, $F_{1,12} = 494.53$, $p < 0.01$, ANOVA). Crested wheatgrass cover was reduced from 55% to less than 1% following herbicide treatment across burns ($p < 0.01$, Tukey HSD). Herbicide with patch burn grazing eliminated cover of crested wheatgrass in all burns, except for 1% remaining at one year since fire. There was no significant interaction between years since fire and patch burn grazing with herbicide given uniform reductions in cover. Plant mortality, related to herbicide efficacy, decreased from 98 to 85% with time since fire (Fig. 3, $p < 0.05$, $r^2 = 21\%$).

Discussion

Combining herbicide with patch burn grazing produced an immediate reduction in crested wheatgrass cover regardless of time since fire. Similar reductions in crested wheatgrass cover as a result of herbicide applications have been demonstrated in grasslands without patch burn grazing (Bakker et al., 1997; Hansen and Wilson, 2006; Wilson and Gerry, 1995; Wilson and Partel, 2003). Surprisingly, reductions in plant cover did not decrease with greater time since fire as anticipated with accumulating biomass and litter within two years of fire (Gates et al., 2017; Vermeire et al., 2011). All of the patches have been focally grazed over the last three years during the growing season immediately following burning. The accumulation of litter may be delayed due to focal grazing even if current year production has recovered, especially for perennial grasses, such as crested wheatgrass. The initial uniform reductions in cover regardless of time since fire may become more variable over time as crested wheatgrass often responds to herbicide with increased plant growth in subsequent years (Bakker et al., 1997; Fansler and Mangold, 2011; Hulet et al., 2010; McAdoo et al., 2017). The overall reductions in cover across the pasture may also be temporary as crested wheatgrass can quickly return to untreated levels within two years of initial herbicide application (Hulet et al., 2010).

While herbicide with patch burn grazing consistently eliminated crested wheatgrass cover regardless of time since fire at the quadrat scale, efficacy of herbicide quantified by plant mortality at the plot scale was significantly lower in patches at two years since fire, reflecting increased variability in plant response at a broader scale. Plant mortality was likely lower in patches at two years since fire as vegetation structure and litter is returning to an unburned state (Gates et al., 2017; Gittins et al., 2011; Vermeire et al., 2011). It is not surprising to detect decreased efficacy with greater time since fire at the larger plot scale where increased litter is more likely to be present and influential. Increased litter obstructs herbicide contact from metabolically active shoots, increasing plant survivorship (Robertson et al., 2013). Though plant mortality was reduced as years since fire increased, mortality rates still remained relatively high at 85%. High precipitation during the week prior to herbicide application increased plant growth and likely increased plant uptake of herbicide (McAdoo et al., 2017; Robertson et al., 2013).

Overall, patch burn grazing without herbicide did not produce a significant change in crested wheatgrass cover. However, cover was maintained in the recent burned patch while it increased by 200% and 150% in patches at one and two years since fire, respectively. The variability in cover across patches reflects shifts in grazing utilization along the gradient of time since fire. After burning in 2016, but prior to patch burn grazing, the recent burned patch had the greatest cover as a result of increased nutrients available postfire (Augustine et al., 2010; Johnson and Matchett, 2001). However, focal grazing during patch burn grazing in the recent burned patch prevented cover from increasing as it did in patches with greater time since fire. Increased consumption of crested wheatgrass likely occurred in the recent burned patch as grazing selection was shifted to the broader patch scale. Cover in the recent burned patch will likely remain below other patches into the start of the next growing season as demonstrated by the current patch at one year since fire. The patch at one year since fire had the lowest cover before patch burn grazing, reflecting the occurrence of focal grazing in the patch during 2015 when it was the recent burned patch. The shift of focal grazing to the most recent burned patch in 2016 allowed cover in the patch at one year since fire to increase nearly two fold, reflecting reduced grazing intensity. The patch at two years since fire increased to a lesser degree, indicating that it is fully recovered from focal grazing that occurred two years prior and that it is currently receiving minor grazing.

The lack of change in crested wheatgrass cover in the recent burned patch without herbicide suggests that fire directly improves palatability by removing litter as cattle avoid it if as few as two dead stems are present (Ganskopp et al., 1993). Increased consumption of crested wheatgrass in pastures with less than one year since fire in the Northern Great Plains has been demonstrated to reduce its frequency (Lodge, 1960) and biomass compared to native species (Gates et al., 2017). However, the pattern of fire and gradient of time since fire in patches available to grazers was likely a greater driver maintaining cover levels in the recent burned patch (Cummings et al., 2007). Concentrated grazing in the recent burned patch will maintain crested wheatgrass in an early phenological state over a longer temporal extent than uniform grazing in a homogenously burned pasture. Grazers often form grazing lawns that are repeatedly grazed due to positive feedbacks between forage quality and herbaceous regrowth in frequently grazed areas (Adler et al., 2001; Archibald, 2008; Hobbs et al., 1991; Lemaire et al., 2000). Patch burn grazing similarly creates positive feedbacks at a larger patch scale as grazers continuously graze recent burns, keeping plants in a state of constant regrowth and early phenology as demonstrated in mesic and semiarid grasslands (Augustine and Derner, 2015; Cummings et al., 2007).

Management Implications

Grazing selection for crested wheatgrass is increased with patch burn grazing without additional fencing to change livestock distribution (Vermeire et al., 2004), along with enhancing structural heterogeneity (Fuhlendorf and Engle, 2001) and maintaining livestock weight gains (Limb et al., 2011). Although grazing alone is likely not enough to control this grazing tolerant species, it may be less resilient to consistent focal grazing with patch burn grazing. In the Northern Great Plains, patch burn grazing shifted grazing selection to a broader scale in recent burned patches that maintained stable cover of crested wheatgrass and potentially other invasive and avoided grasses, such as Japanese brome (*Bromus japonicas*) and Kentucky bluegrass (*Poa pratensis*). Herbicide with patch burn grazing reduced crested wheatgrass cover over a short temporal window with increased efficacy in patches burned within one year since fire, demonstrating that applying herbicide within one year of fire and grazing may enhance treatments at a larger scale. Increased efficacy of herbicide applied with patch burn grazing in the recent burned patch aligns with the current large scale treatment of crested wheatgrass by federal agencies in the Northern Great Plains using prescribed fire followed by herbicide (Northern Broadcasting System, 2016). Though our study occurred during an abnormally wet spring, similar results with herbicide application in the early spring with patch burn grazing are likely as crested wheatgrass is more influenced by management than fluctuations in precipitation (Hansen and Wilson, 2006). Crested wheatgrass may be successfully managed with patch burn grazing in the short term as a result of improved palatability and the shifted scale of grazing selection. However, the combination of herbicide with patch burn grazing is likely required to effectively control crested wheatgrass where it is intermixed with native prairie. Dense infestations of crested wheatgrass may require multiple treatments of herbicide with patch burn grazing over several years for a successful restoration to native grassland (McAdoo et al., 2017). Additional research over longer temporal scales is needed to determine the full response of crested wheatgrass to these management techniques and the trajectory of vegetation succession following its removal.

Figures

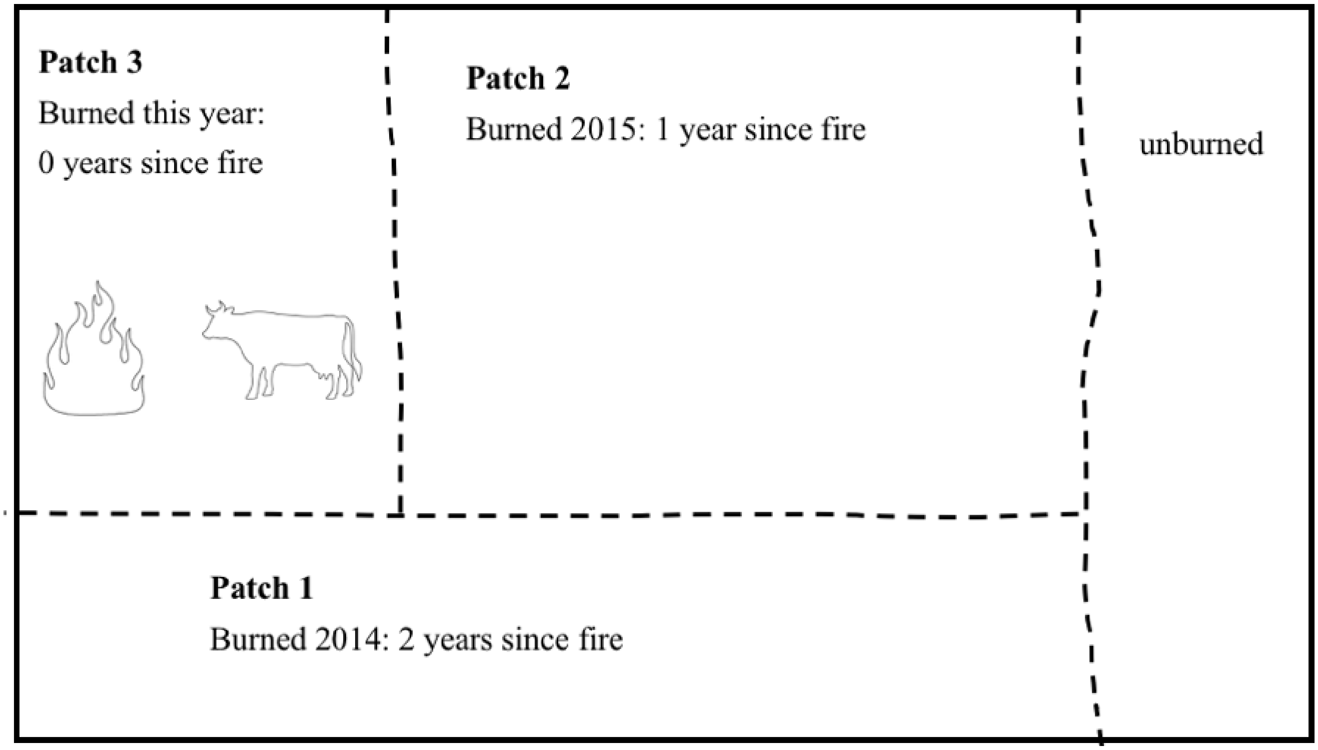

Figure 1. Patch burn grazing study design in a 355 ha pasture in the Northern Great Plains in 2016. Five paired herbicide and control plots (5 x 5 m) are located in each burn patch. Solid lines indicate pasture fence boundaries; dotted lines indicate patch location of fires. Years since fire of each patch is indicated. Flame and cattle represent location of current years' burn with increased cattle utilization.

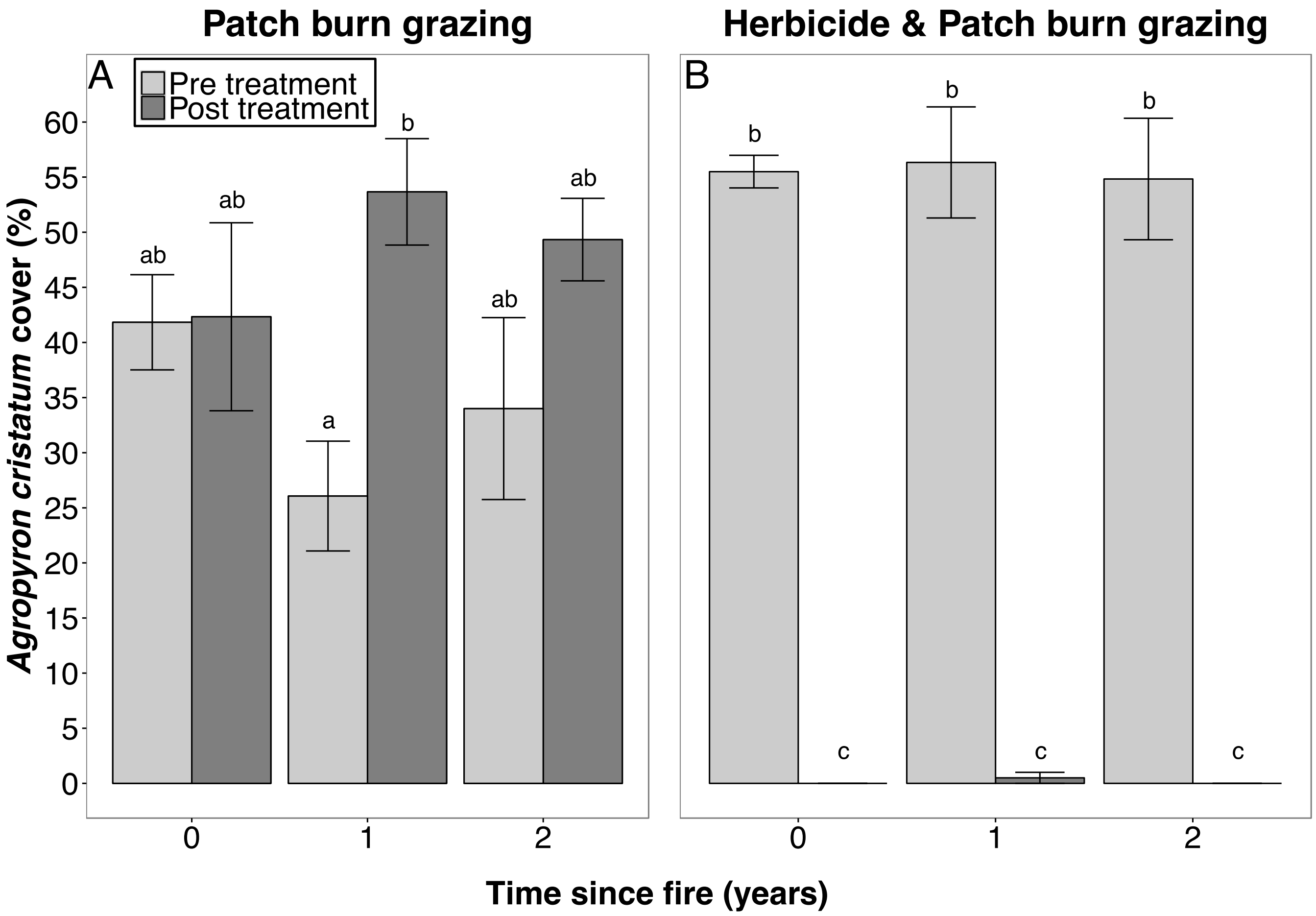

Figure 2. Cover of *Agropyron cristatum* (%) at the quadrat level in patches varying in time since fire (years) in the Northern Great Plains (n=5 plots per burn) treated with either patch burn grazing (A) or herbicide and patch burn grazing (B). Letters indicate significant differences within treatments ($p < 0.05$, Tukey HSD). Error bars represent one standard error.

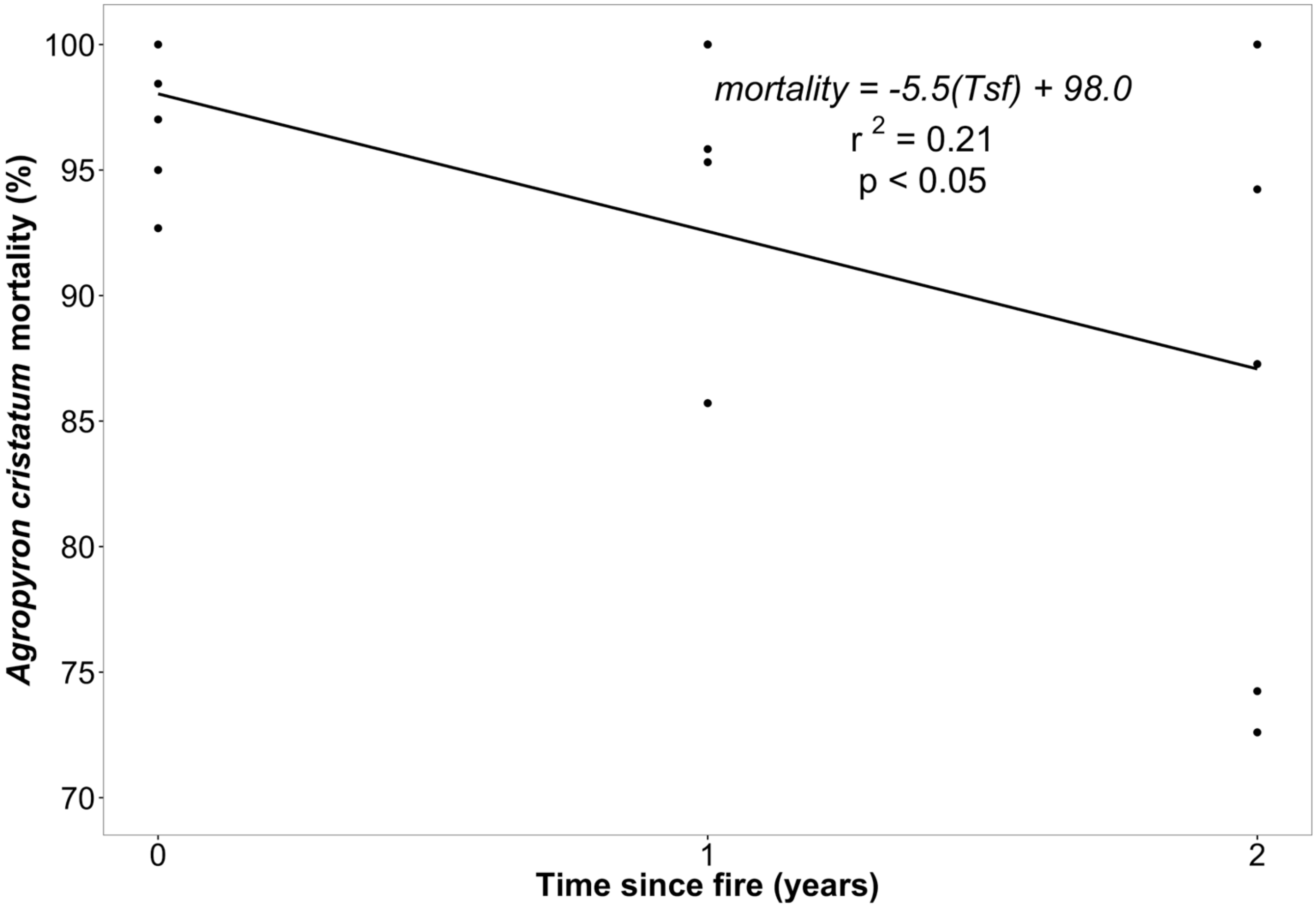

Figure 3. Relationship between time since fire (years) and *Agropyron cristatum* mortality (%) indicating herbicide efficacy across treated plots in pasture managed with patch burn grazing in the Northern Great Plains (n=5 plots per burn patch).

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