Received: 12 June 2024 | Revised: 28 April 2025 | Accepted: 6 August 2025

DOI: 10.1111/csp2.70128

CONTRIBUTED PAPER

Conservation Science and Practice
A journal of the Society for Conservation Biology
Open Access

WILEY

Comparing the impacts of patch-burn grazing on vegetation in two northern tallgrass prairies

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Funding information
Minnesota Environment and Natural Resources Trust Fund; Minnesota DNR Game and Fish Fund

Abstract

The management practice of patch-burn grazing varies grazing pressure across a site by rotating burn locations, thereby creating spatial heterogeneity in vegetation height and structure. Patch-burn grazing increases the range of habitats available for different wildlife species, but it may also affect plant invasion and plant biodiversity. We evaluated the effects of patch-burn grazing on plant communities in two northern tallgrass prairies that were undergoing invasion by the non-native grass smooth brome (*Bromus inermis* Leyss) and had different cattle stocking rates and burning practices (three or five burn units). We established 15–20 plots per site for each treatment of patch-burn grazing (open) and burning-without-grazing (fenced). We measured vegetation structure, native and non-native plant richness, smooth brome frequency, and frequency-weighted mean coefficients of conservatism (mean *C*) over 5–6 years. At the site with a lower stocking rate and more burn units, grazing promoted spatial heterogeneity by reducing vegetation structure 18%–65% points in some units and some years. In both treatments, native richness increased 15% over 6 years; non-native richness did not change, but smooth brome frequency increased over 200%. At the site with a higher stocking rate and fewer burn units, grazing reduced vegetation structure 37%–78% points in all units and all years, but native richness was maintained over time. Grazing also increased non-native richness 38% points but did not change mean *C* calculated without non-natives. Smooth brome frequency increased 2% over 2 years in both treatments. We suggest that patch-burn grazing can achieve structural heterogeneity and sustain native plant species richness in small northern tallgrass prairie remnants; however, higher stocking rates can stimulate the emergence of non-native species present in the seed bank from past land use, and patch-burn grazing would not be effective in suppressing the smooth brome invasion that threatens many northern tallgrass prairie remnants.

KEYWORDS

grazing, management, native prairie, patch-burn grazing, smooth brome, species richness

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1 | INTRODUCTION

The temperate grasslands biome is among the most-endangered, least-protected major habitat types on Earth (Hoekstra et al., 2005). Much of North America's original tallgrass prairie (Figure 1), which is in the eastern Great Plains and extended east to Ohio, was converted to crops because it had some of the world's richest agricultural soils (Hoekstra et al., 2005; Samson & Knopf, 1994). For example, Minnesota, United States, had approximately 18 million acres of native tallgrass prairie when European-Americans began colonizing the state in the mid-to-late 1800s (Marschner, 1974), but less than 1.4% of its original native prairie remains today, often in the form of small, isolated fragments (Minnesota Biological Survey [MBS], 2017). Historically, fires and herds of grazing animals helped maintain prairies (Anderson, 2006), but management practices that simulate these disturbances can be difficult or potentially harmful to implement on small fragments. Therefore, management practices that have been developed in more expansive grasslands must be evaluated for appropriate use within remaining small, fragmented prairies.

In Great Plains rangelands where larger grassland patches remain (Samson & Knopf, 1994), managers have a tradition of managing prairies with cattle grazing (Anderson, 2006). In more fragmented eastern portions of tallgrass prairie, such as Minnesota, Wisconsin, Iowa, and Missouri (Samson & Knopf, 1994), managers historically have not used grazing on conservation lands due to concerns about negative impacts and logistical constraints (Dixon et al., 2019; Larson et al., 2020). Many native prairie remnants on conservation lands in the eastern portions of the tallgrass prairie were protected for their diversity and abundance of "conservative" plant species (species that decrease with grazing, as described by Weaver 1954). Therefore, some prairie conservationists in this region expressed concerns about the potential loss of conservative species due to management with cattle grazing (Curtis, 1959; Dix, 1959; Drew, 1947; Leach et al., 1999). In addition, lower livestock numbers are required to achieve conservation goals on smaller management areas, often leading to less profit for the livestock producers; especially as fencing and water supply are often more difficult on small units (Larson et al., 2020). Despite these challenges, prairie managers in Minnesota are exploring grazing as a strategy to help meet their management goals of promoting heterogeneity of vegetation structure, floristic diversity, and native prairie species while suppressing non-native species (Ahlering et al., 2020).

One of the primary management goals for Minnesota tallgrass prairies is to suppress cool-season (C_3) non-native grasses, such as smooth brome. Smooth brome expands in prairies in the absence of disturbance and may develop more extensive invasions in smaller prairie fragments due to edge effects (Dekeyser et al., 2013; Grant et al., 2009). Smooth brome negatively affects the abundance of native plant species (Palit & De Keyser, 2022), including pasqueflower (*Anemone patens* L.) (Williams & Crone, 2006) and prairie cordgrass (*Spartina pectinata* Link) (Dillemuth et al., 2009). Some research indicates that late-spring burns may suppress smooth brome during a potentially vulnerable growth stage (Willson & Stubbendieck, 2000; but see Gannon et al., 2025). Intensive late-spring grazing could also potentially suppress smooth brome, and may explain negative correlations between grazing and smooth brome across prairies (Coleman et al., 2023; Larson et al., 2020). However, as a forage species, smooth brome is likely adapted to light or moderate grazing (Brudvig et al., 2007; Salesman & Thomsen, 2011).

Another primary management goal for Minnesota tallgrass prairies is promoting floristic diversity, especially through conservation of native prairie species (Ahlering et al., 2020). Many ecological studies find that grazing management increases total plant species richness (Gao & Carmel, 2020). Cattle grazing can also lessen the abundance of dominant warm-season (C_4) grasses and increase native plant richness (Brudvig et al., 2007; Hickman et al., 2004). However, cattle grazing in the northern tallgrass prairie has also been associated with lower native plant recruitment (Ahlering et al., 2020), higher non-native plant species richness and cover (Brudvig et al., 2007; McGranahan, Engle, Wilsey, et al., 2012), and no change in native plant conservatism (an index that is higher for species more sensitive to habitat degradation and more confined to a narrow range of microhabitat conditions) (Brudvig et al., 2007; Larson et al., 2020).

A grazing strategy that may help achieve multiple prairie management goals, including maintaining native plant diversity, is patch-burn grazing (Duquette et al., 2022; Fuhlendorf & Engle, 2004). In patch-burn grazing, livestock have season-long, open access (no interior fences) to a large site subdivided into several burn units (Fuhlendorf & Engle, 2001, 2004). The strategy acknowledges the historical interaction of burning and grazing in prairie ecosystems (Anderson, 2006) and aims to create the natural shifting mosaic of vegetation that many plants and animals are adapted to (Fuhlendorf & Engle, 2001). The years of non-focused grazing or rest in unburned units in patch-burn grazing may allow prairies to sustain grazing-sensitive, conservative plant species (Briggler et al., 2017) that would be eliminated by heavy, annual grazing. However, it should be noted that burning at times other than late spring to accommodate cattle during patch-burn grazing is not

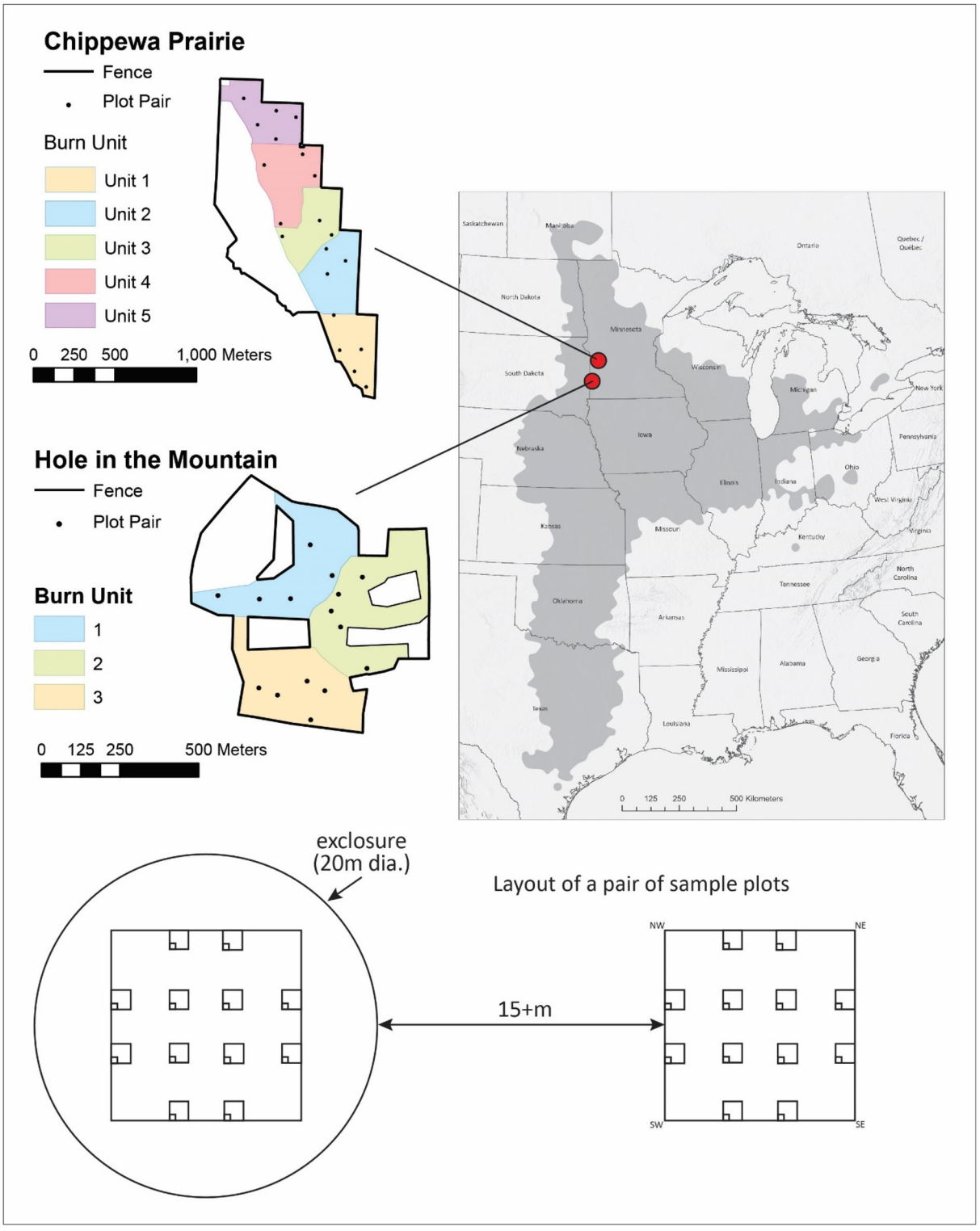


FIGURE 1 Maps of the Chippewa Prairie and Hole in the Mountain study sites and their locations within the former extent of tallgrass prairie in North America (*Source*: NatureServe 2025). Each study site has a perimeter fence and is divided into different burn units. Dots within burn units are pairs of 10 m × 10 m, permanently marked vegetation plots. One member within each pair of vegetation plots is fenced off from grazing with a circular fence "exclosure"), the other plot is open to grazing. Each vegetation plot was sampled in twelve 1 m^2 quadrats, each of which contains a nested 0.1 m^2 quadrat. The quadrats were aligned along the sides and perimeters of each plot.

expected to suppress smooth brome (Duquette et al., 2022; Salesman & Thomsen, 2011).

Given the potential for mixed effects of grazing on management goals in Minnesota's tallgrass prairie, it is unclear how well patch-burn grazing will help managers promote native plant species while suppressing non-native species. To isolate and evaluate the effects of grazing within the patch-burn grazing management strategy, we compared patch-burn grazing to burning-without-grazing on two sites in Minnesota with different grazing intensity and burn frequency. We evaluated the effects of patch-burn grazing on metrics that managers aim to maximize: heterogeneity of vegetation structure, native plant richness, and the mean coefficient of conservatism. We also evaluated the effects of patch-burn grazing on metrics that managers aim to minimize: non-native plant richness and smooth brome frequency.

2 | METHODS

2.1 | Study areas

The 639 ha Chippewa Prairie is in Swift and Chippewa Counties, Minnesota (Latitude 45.143853° N; Longitude −95.99967° W). It is managed by The Nature Conservancy and the Minnesota Department of Natural Resources. The 215 ha Hole in the Mountain Wildlife Management Area is in Lincoln County, Minnesota (Latitude 44.44237° N; Longitude −96.30898° W), where it is managed by the Minnesota Department of Natural Resources.

Both remnant prairie sites occur on deep, well-drained, calcareous loam soils formed in glacial till from the Des Moines Lobe glaciation (Ves, Svea, and Buse series—Natural Resources Conservation Service [NRCS], 2016). Native plant communities in both sites are predominantly dry-mesic prairie dominated by big bluestem (*Andropogon gerardii* Vitman), porcupine grass (*Hesperostipa spartea* [Trin.] Barkworth), Indian grass (*Sorghastrum nutans* L. Nash), leadplant (*Amorpha canescens* Pursh), little bluestem (*Schizachyrium scoparium* (Michx.) Nash), and sideoats grama (*Bouteloua curtipendula* [Michx.] Torr.). Smooth brome was widely planted across Minnesota, and it dominates roadsides in the vicinity of the two study areas in this project.

Slopes range from level to moderate at Chippewa Prairie, and level to moderately-steep at Hole in the Mountain. Chippewa Prairie was mostly grazed with cattle but portions were traditionally hayed before it was acquired in 1971. Hole in the Mountain WMA (wildlife management area) was grazed with cattle before it was acquired in 1991. Each site was managed for more than two decades as natural areas without grazing. Chippewa Prairie had burns once every 3–5 years. Controlled burns were much less frequent at Hole in the Mountain WMA.

2.2 | Management

Patch-burn grazing was initiated by site managers at Chippewa Prairie in 2012 and at Hole in the Mountain in 2018. Both projects were intended to enhance wildlife habitat diversity, maintain native prairie vegetation, and suppress non-native plant species. These projects are among the first attempts to manage prairie with patch-burn grazing in Minnesota. For each site, a fence was constructed around the perimeter of the area to receive grazing management, with open access and no internal fencing between burn units (Figure 1). Chippewa Prairie was divided into five burn units ranging from 114 to 148 ha. Hole in the Mountain started with four burn units for the first 2 years; then one unit was removed and another unit was reduced in size, resulting in three burn units ranging from 28 to 42 ha. Livestock numbers at Hole in the Mountain were reduced in proportion to the reduction in burn units. We report results from only these three final burn units for Hole in the Mountain. At each site, each burn unit was burned in a different year in late April to early May.

Grazing was accomplished with cow-calf pairs or heifers, with a few bulls, released 2–3 weeks after a burn and left to graze for 2.5–3.5 months within the fenced grazing management area. The livestock were provided by local producers under grass banking agreements in which producers rested, and in some years burned, their home pastures in exchange for grazing on conservation land. Pasture sizes, burn unit numbers, burn unit sizes, and stocking rates for the two sites are presented in Table 1 and illustrated in Figure 1. The stocking rate at Hole in the Mountain was two to three times the rate at Chippewa Prairie.

2.3 | Plot selection and data collection

The objective of this study was to examine community responses to two treatments: patch-burn grazing and burning-without-grazing in each of two sites. In order to compare treatments, we established and first sampled pairs of vegetation plots before the year that patch-burn grazing was initiated. Within each pair of vegetation plots, one plot was enclosed within a permanent circular exclosure so that it served as an ungrazed control for comparison to the grazed plot within each pair (Figure 1). Locations of plot pairs (i.e., statistical blocks)

TABLE 1 Total fenced pasture hectares, burn unit hectares, number of burn units, total fenced and burned hectares per animal unit (AU), and animal unit months (AUM) per total fenced and burn unit hectares under patch-burn grazing in two study sites. One animal unit (AU) is a 1000 lb. cow.

Site	Total pasture ha (burn ha)	No. of burn units	Pasture ha/AU (burn ha/AU)	AUM/ha (AUM/burn ha)
Chippewa Prairie	736 (115–149)	5	2.6–3.9 (0.5–0.7)	0.8–1.3 (4.7–8.2)
Hole in the Mountain	101–130 (28–42)	3–4	1.1–1.2 (0.4–0.5)	2.2–3.7 (5.6–17.1)

were randomly sited in dry-mesic prairie within each burn unit with a minimum of 150 m between plot pairs. For each selected location, two 10 m × 10 m permanent plots were sited in the same positions in the landscape (e.g., elevation and aspect) and a minimum separation distance of 15 m between plots. The corners of each plot were permanently marked with buried markers. Cattle exclosures randomly assigned to one member of each plot pair consisted of 20 m-diameter circles constructed from cattle panels affixed to t-posts. The exclosure fence was 2.9 m from the corners and 5 m from the sides of the 100 m^2 plot it encircled. Twenty plot pairs were established in five burn units at Chippewa Prairie (3–5 blocks per unit); 15 plot pairs were established in three burn units at Hole in the Mountain (5 blocks per unit). The minimum number of blocks established per unit (3) was informed by a simulation-based power analysis conducted in 2011, which used preliminary data from Chippewa Prairie and assumed a change in frequency of 18% for each of 16 taxa.

Vegetation sampling took place in the last week of July or first 2 weeks of August in each sampled year. We refer to the first year of patch-burn grazing as "experiment year 1." Chippewa Prairie was sampled in 2011, 2013, 2014, and 2017 (experiment years 0, 2, 3, and 6, respectively). Hole in the Mountain was sampled in 2016, 2019, and 2022 (experiment years −1, 2, and 5). Vegetation structure was assessed using the Visual Obstruction Reading (VOR) method following the procedure of Robel et al. (1970). With the observer located 4 m away with their eye at 1 m above ground, we recorded the lowest 5 cm increment of a calibrated PVC (polyvinyl chloride) pole at the plot center that was not completely obscured by vegetation. Four VOR readings were sighted for each plot with one from each cardinal direction. To quantify species frequency for each 10 m × 10 m plot, we visually observed and recorded all plant species, or species groups for a few difficult taxa, that were present in twelve 1 m^2 quadrats per plot, and in a 0.1 m^2 quadrat nested in one corner of each quadrat. The nested quadrats were sampled to assess change in frequency of a few highly abundant species. The quadrats were placed along the perimeter and diagonals of each plot (Figure 1).

2.4 | Data analysis

Native and non-native richness (excluding smooth brome) were tallied for each quadrat, with nomenclature based on The State of Minnesota Vascular Plant Checklist (Minnesota Department of Natural Resources [MNDNR], 2015).

Coefficient of conservatism (C_i) values for Minnesota prairie species were obtained from the Minnesota Department of Natural Resources (Minnesota Biological Survey [MBS], 2022). Non-native species were assigned a C_i value of zero (smooth brome excluded from analyses). We calculated frequency-weighted mean coefficient of conservatism ($\overline{C}_r$) for each plot, hereafter "mean C," adapted from Freyman et al. (2016), in which C_i is the coefficient of conservatism for taxon i, θ_i is the proportion of quadrats in which taxon i was present, and n is the number of taxa in the plot:

$$\overline{C}_r = \frac{\sum_{i}^{n}(C_i\theta_i)}{\sum_{i}^{n}\theta_i}.$$

Weighting mean C by frequency distinguishes between plots with the same plant species, assigning a higher value to the plot in which conservative species are more common. We calculated frequency-weighted mean C excluding and including non-native species.

We fit generalized linear mixed effects models to evaluate the effect of patch-burn grazing on each response variable (i.e., VOR, native and non-native plant richness, brome frequency in quadrats and nested quadrats, and mean C) relative to burning-without-grazing. The explanatory variables were grazing treatment (binary), year of data collection (categorical), and the interaction between grazing treatment and year. The random intercept was quadrat within plot, within block, within unit for native and non-native plant richness and plot within block, within unit for the other response variables. Separate models were fit for each site. The intercept represented pre-treatment measurements in burning-without-grazing plots. The interaction coefficient estimated the effect of grazing on the change in the response since

pre-treatment. To evaluate whether recent burning modified the strength of the patch-burn grazing effect, we refit models with an additional explanatory variable for burn unit, which had a three-way interaction with grazing treatment and year. To ease interpretation, if the two-way interaction was statistically significant, we fit the above-described model, with a two-way interaction between grazing treatment and year, separately for each unit. The response distributions were lognormal (log-link) for vegetation structure and mean *C*, Poisson (log-link) for native and non-native richness, and binomial (logit-link) for brome frequency. We fit models using the glmmTMB package (Brooks et al., 2017) in R version 4.2.2 (R Core Team, 2022). We evaluated model fit using a non-parametric overdispersion test and residual diagnostics with the DHARMa package (Hartig, 2022). In the results, we report the effect sizes (eff.) as the percentage change in the estimated marginal means (Lenth et al., 2024). To quantify the effect of grazing on change over time, we subtracted the percentage change over time for burning-without-grazing from the percentage change over time for patch-burn-grazing (diff.). Note that we therefore refer to the comparison between treatments as the "effect of grazing" and the treatments as "grazing treatments" because both treatments had prescribed burning, but only patch-burn grazing had grazing. Figures depict the mean and bootstrapped 95% confidence intervals (CI) of the raw data.

We fit a hierarchical Bayesian binomial (probit-link) model to presence/absence data of each taxon in each plot to evaluate the effects of patch-burn grazing on individual taxa, using the Hmsc package in R (Tikhonov et al., 2020). The explanatory variables were grazing treatment, year, and their interaction. Origin was included as a trait. Intercepts and coefficients for all taxa per site were simultaneously estimated in one model. We used default priors (appendix S1 of Tikhonov et al., 2020) and fit models with three chains of 1000 samples with 500 burn-in samples and a thinning rate of 10 samples. Model fits were evaluated with potential scale reduction factors and effective sample sizes. Model estimates and 95% credible intervals are on the *z*-score scale. Functional groups were assigned to each taxon highlighted in the results (Natural Resources Conservation Service [NRCS], 2024).

3 | RESULTS

3.1 | Visual Obstruction Reading

At Chippewa Prairie, the standard deviation in VOR across units was 1.5 dm pre-treatment (Figure 2a, Appendix S1). The standard deviation in VOR across units was sometimes higher with patch-burn grazing (0.6, 0.3, and 0.6 dm in Years 2, 3, and 6, respectively) than burning-without-grazing (0.3, 0.6, and 0.4 dm in Years 2, 3, and 6, respectively). In unit 3 (burned year 5), VOR declined 49% in patch-burn grazing plots by Year 3; but only 2% in burning-without-grazing plots, a net grazing effect of −47% points ($p = .03$). Grazing did not affect VOR in unit 3 years other than 3, or units 2 and 4 in any year. In unit 5, grazing reduced VOR 70% points in the year it was burned (Year 2; $p < .001$) and 33% points in Year 6 ($p = .02$), but VOR was not significantly affected by grazing in Year 3. In unit 1, grazing reduced VOR 29% points in Year 2 (3 years post-burn; $p = .006$), 30% points in Year 3 (4 years post-burn; $p = .004$), and 19% points in Year 6 (7 years post-burn; $p = .03$) (Figure 2).

At Hole in the Mountain, the standard deviation in VOR across units was 0.5 dm pre-treatment (Figure 2b, Appendix S2). The standard deviation in VOR across units was not always higher with patch-burn grazing (0.9 and 0.6 dm in Years 2 and 5, respectively) compared to burning-without-grazing (0.5 and 0.8 dm in Years 2 and 5, respectively). Patch-burn grazing significantly reduced VOR in all 3 units relative to burning-without-grazing, regardless of burn timing. In unit 1 (burned in Years 1 and 5), grazing reduced VOR 45% points in Year 2 ($p < .001$) and 53% points in Year 5 ($p = .004$). In unit 2 (burned in Year 4), grazing reduced VOR 45% points in Year 2 ($p = .004$) and 53% points in Year 5 ($p < .001$). In unit 3, which was never burned, grazing reduced VOR 51% points in Year 2 ($p < .0001$) and 55% points in Year 5 ($p < .0001$).

3.2 | Native plant richness

Patch-burn grazing did not significantly affect native plant richness at either site relative to burning-without-grazing. At Chippewa Prairie, average native plant richness pre-treatment was 12.8 taxa (Figure 3a, Appendix S3). Native richness in burning-without-grazing plots increased 8% by Year 2 ($p = .002$), 14% by Year 3 ($p < .001$), and 15% by Year 6 ($p < .001$). Native richness did not significantly differ between patch-burn grazing and burn-without-grazing treatments during the pre-treatment survey (eff. = 4%, $p = .2$); patch-burn grazing did not significantly affect the change in native richness over time (2 years: diff. = −2% points, $p = .6$; 3 years: diff. = −1% points, $p = .8$; 6 years: diff. = +2% points, $p = .7$).

At Hole in the Mountain, average native plant richness pre-treatment was 7.6 taxa (Figure 3b, Appendix S4). Native richness did not significantly change over time (2 years: eff. = −3%, $p = .4$; 5 years: eff. = −4%, $p = .3$)

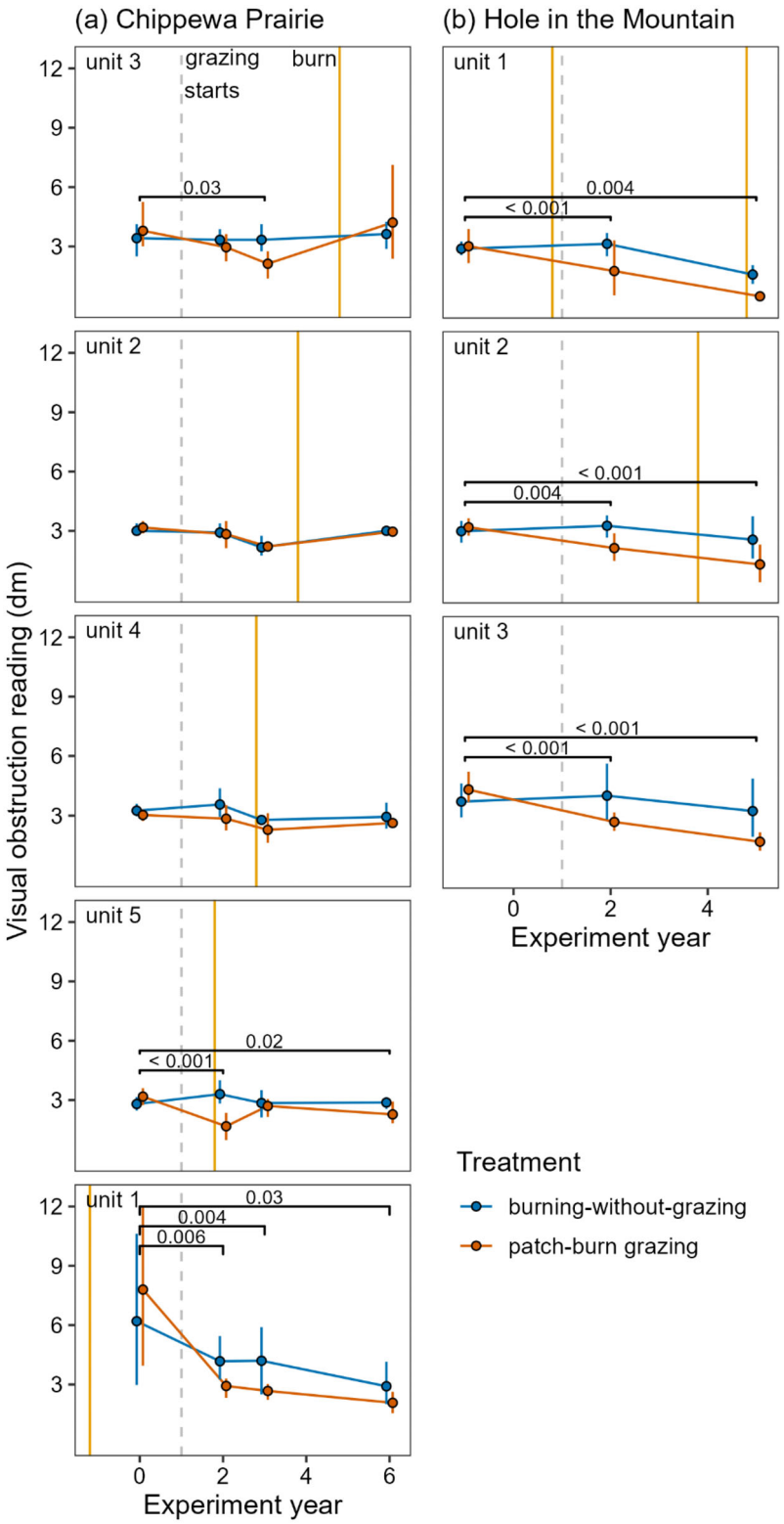


FIGURE 2 Average (±95% confidence interval) of raw data of Visual Obstruction Reading (VOR), a measurement of vegetation structure, per unit over time for patch-burn grazing and burning-without-grazing in (a) Chippewa Prairie and (b) Hole in the Mountain. The gray vertical dashed lines at experiment Year 1 indicate when grazers were introduced to the sites and the left-most points are the pre-treatment survey measurements. The orange vertical solid lines indicate the year that each unit was burned. Brackets indicate statistically significant interactions between treatment and experiment year with *p* values denoted on top (Appendices S1 and S2). Brackets start at the pre-treatment survey and end at the year in which a significant interaction was measured. Units are organized from top-to-bottom as most recent burn to oldest burn (if any).

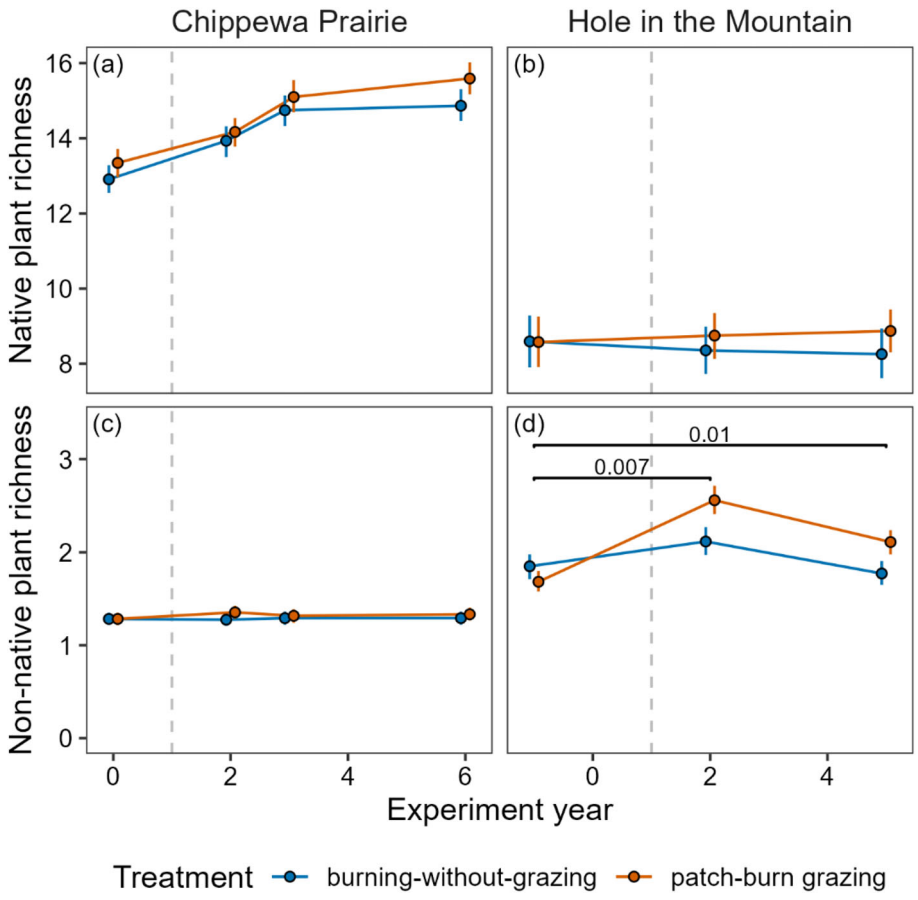


FIGURE 3 Average (±95% confidence interval) of raw data of native (a, b) and non-native (c, d) plant species richness per 1 m^2 quadrat over time for patch-burn grazing and burning-without-grazing in Chippewa Prairie (a, c) and Hole in the Mountain (b, d). The gray vertical dashed lines at Year 1 indicate when grazers were introduced to the sites and the left-most points are the pre-treatment survey measurements. Brackets indicate statistically significant interactions between treatment and experiment year with *p* values denoted on top (Appendix S8). Brackets start at the pre-treatment survey and end at the year in which a significant interaction was measured.

and did not significantly differ between patch-burn grazing and burn-without-grazing treatments during the pre-treatment survey (eff. = 1%, $p = .8$). Though there were trends of decreasing richness in the burning-without-grazing plots and increasing richness in patch-burn grazing plots, patch-burn grazing did not significantly affect the change in native richness over time (2 years: diff. = +5% points, $p = .3$; 5 years: diff. = +7% points, $p = .1$). For both sites, results held even when units with different burn timings were evaluated separately (Appendices S5 and S6) (Figure 3).

3.3 | Non-native plant richness

Patch-burn-grazing affected non-native plant richness relative to burning-without-grazing at Hole in the Mountain, but not Chippewa Prairie. At Chippewa Prairie, average non-native plant richness pre-treatment was 1.3 taxa (Figure 3c, Appendix S7). Non-native richness did not significantly change over time (2 years: eff. = −1%, $p = .9$; 3 years: eff. = 1%, $p = .9$; 6 years eff. = 1%, $p = .9$) and did not significantly differ between grazing treatments during the pre-treatment survey (eff. = 0%, $p = 1.0$). Patch-burn grazing did not significantly affect the change in non-native richness over time (2 years: diff. = +6% points, $p = .6$; 3 years: diff. = +2% points, $p = .9$; 6 years: diff. = +3% points, $p = .8$).

At Hole in the Mountain, average non-native plant richness pre-treatment was 1.8 taxa (Figure 3d, Appendix S8). In burning-without-grazing plots, non-native richness increased 14% by Year 2 and declined 4% by Year 5. In patch-burn-grazing plots, non-native richness increased 52% by Year 2 and 25% by Year 5. Therefore, patch-burn grazing increased non-native species richness 38% points by Year 2 ($p = .007$) and 30% points by Year 5 ($p = .01$). For both sites, the strength of patch-burn grazing did not vary significantly across units (Appendices S9 and S10).

3.4 | Smooth brome frequency

Patch-burn-grazing did not significantly affect smooth brome frequency at either site relative to burning-without-grazing. At Chippewa Prairie, average smooth brome frequency pre-treatment ranged from 0.004 to 0.5, with high variation among blocks (SD = 2.7, Appendix S11). In burning-without-grazing plots, smooth brome

frequency increased 59% by Year 2 ($p = .09$, Figure 4a), 47% by Year 3 ($p = .16$), and 212% by Year 6 ($p < .001$). During the pre-treatment survey, smooth brome frequency was 89% lower in plots assigned to the patch-burn-grazing compared to burning-without-grazing ($p = .008$). Patch-burn grazing did not significantly affect the change in smooth brome frequency over time (2 years: diff. = −19% points, $p = .8$; 3 years: diff. = +38% points, $p = .7$; 6 years: diff. = +203% points, $p = .4$).

At Hole in the Mountain, average smooth brome frequency pre-treatment ranged from 0.002 to 1, with high variation among blocks (SD = 5.5, Appendix S12). In burning-without-grazing plots, smooth brome frequency increased 2% by Year 2 ($p = .07$, Figure 4b) and 2% by Year 5 ($p = .01$). Smooth brome frequency did not significantly differ between patch-burn grazing and burning-without-grazing treatments during the pre-treatment survey (eff. = 1%, $p = .8$). Patch-burn grazing did not significantly affect smooth brome frequency over time (2 years: diff. = −1% point, $p = .8$; 5 years: diff. = 0% points, $p = .8$). For both sites, results held even when units with different burn timings were evaluated separately (Appendices S13 and S14). We found similar patterns when we evaluated smooth brome frequency within nested quadrats (Figure 4c,d, Appendices S15–S18).

3.5 | Frequency-weighted mean *C*

Patch-burn grazing did not significantly affect frequency-weighted mean *C* (native species only) relative to burning-without-grazing at either site. At Chippewa Prairie, average mean *C* pre-treatment was 5.6 (Figure 5a, Appendix S19). In burning-without-grazing plots, mean *C* increased 1% by Year 2 ($p = .04$), 1% by Year 3 ($p = .9$), and 0% by Year 6 ($p = .5$). Mean *C* did not significantly differ between the two treatments during the pre-treatment survey (eff. = 0%, $p = .8$); patch-burn grazing treatments did not significantly affect the change in mean *C* over time (2 years: diff. = 0% points, $p = .5$; 3 years: diff. = 0% points, $p = .8$; 6 years: diff. = 0% points, $p = .7$). These results were similar when non-native species were included in mean *C* (Figure 5c, Appendix S20).

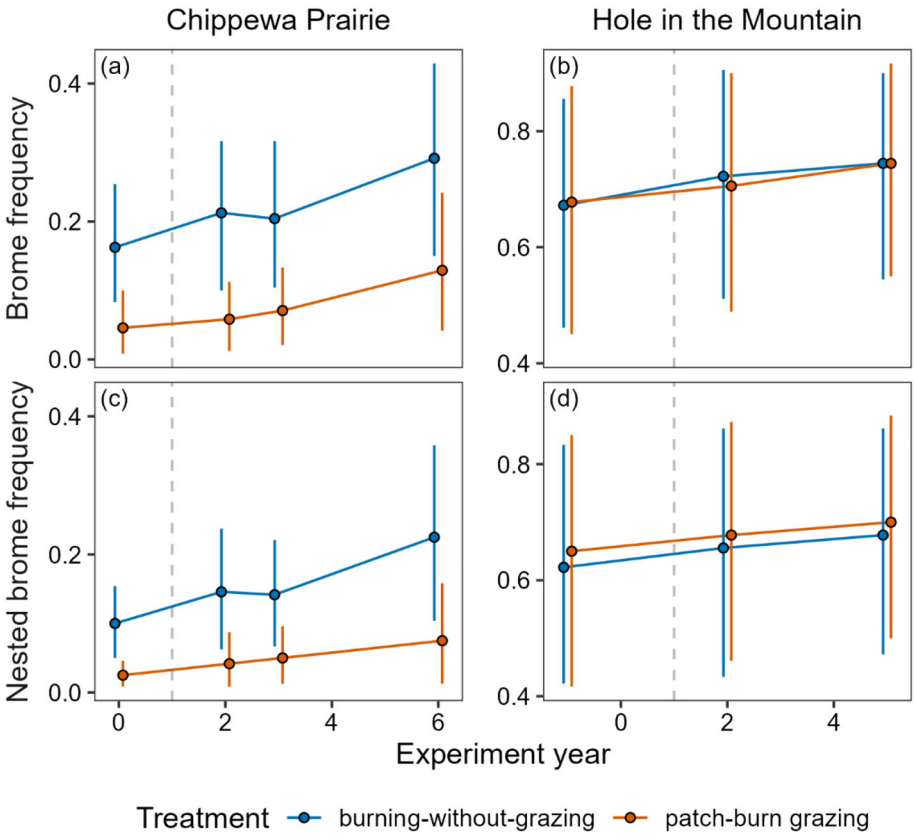


FIGURE 4 Average (±95% confidence interval) of raw data of frequency of smooth brome (*Bromus inermis*) per plot in 1 m^2 quadrats (a, b) and nested (0.1 m^2) quadrat (c, d) over time for patch-burn grazing and burning-without-grazing in Chippewa Prairie (a, c) and Hole in the Mountain (b, d). The gray vertical dashed lines at Year 1 indicate when grazers were introduced to the sites and the left-most points are the pre-treatment survey measurements. Note the separate y-axes for the two sites.

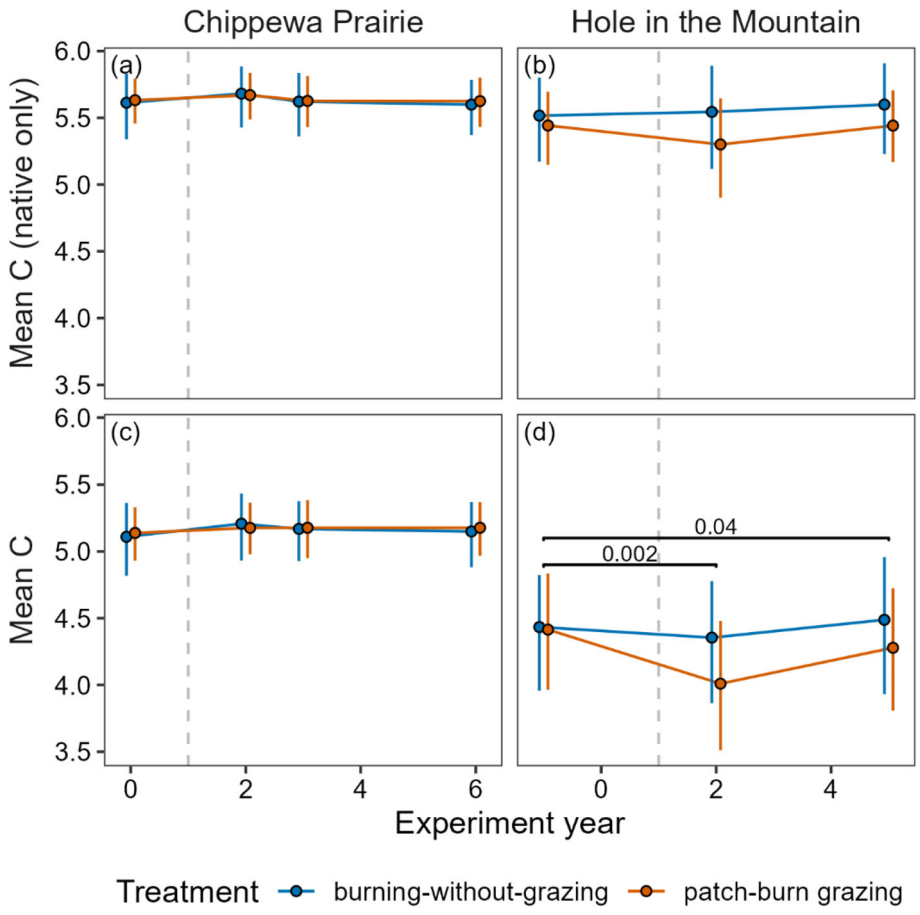


FIGURE 5 Average (±95% confidence interval) of raw data of frequency-weighted coefficient of conservatism with only native species (a, b) and with all species (c, d) per plot over time for patch-burn grazing and burning-without-grazing in Chippewa Prairie (a, c) and Hole in the Mountain (b, d). The vertical dashed lines at Year 1 indicate when grazers were introduced to the sites, and the left-most points are the pre-treatment survey measurements. Brackets indicate statistically significant interactions between treatment and experiment year, with *p* values denoted on top (Appendix S22). Brackets start at the pre-treatment survey and end at the year in which a significant interaction was measured.

At Hole in the Mountain, average frequency-weighted mean *C* (native species only) pre-treatment was 5.5 (Figure 5b, Appendix S21). In burning-without-grazing plots, mean *C* increased 1% by Year 2 ($p = .6$) and 2% by Year 5 ($p = .3$). Mean *C* did not significantly differ between patch-burn grazing and burn-without-grazing treatments during the pre-treatment survey (eff. = 1%, $p = .6$); grazing treatments did not significantly affect the change in mean *C* over time (2 years: diff. = −3% points, $p = .1$; 5 years: diff. = −2% points, $p = .4$). When non-native species were included in mean *C*, the interaction between experiment year and grazing treatment was statistically significant, and patch-burn grazing decreased mean *C* 7% points by Year 2 ($p = .002$) and 5% points by Year 5 ($p = .04$) (Figure 5d, Appendix S22). For both sites, the strength of patch-burn grazing did not vary significantly across units (Appendices S23–S26).

3.6 | Species-specific responses

At Chippewa Prairie, the increase in native plant richness over time was driven by increases in plot occupancy of five native species—four perennial and one biennial—regardless of grazing treatment (Table 2). Only one species increased in Year 6, with all other increases occurring in Years 2 and 3. Five native species—two perennial C_3 grasses and three forbs—decreased in plot occupancy. One non-native annual/short-lived perennial forb increased in plot occupancy by Years 2 and 3. The occurrences of the remaining species were insensitive to time (Appendix S27).

At Hole in the Mountain, species richness did not significantly change over time in the burn-without-grazing treatment; however, the positive effect of the patch-burn grazing treatment on the change in non-native richness over time was driven by increases in the plot occupancy of 14 species of forbs, three perennial C_3 grasses, and a tree (Table 3). The change in occurrences of the remaining species was insensitive to grazing (Appendix S28). Nine of the species that increased in response to patch-burn grazing at Hole in the Mountain were also present in plots at Chippewa Prairie, where they did not respond to patch-burn grazing: Canada thistle, horseweed, quackgrass, sweet clover species, timothy, common dandelion, goat's beard, red clover, and white clover (Appendix S27).

Table 4 summarizes the effects of patch-burn-grazing on the response variables examined in this study.

TABLE 2 Taxa at Chippewa Prairie that changed in plot occupancy over time and their z-score coefficient estimates (and 95% credible intervals) for each time point.

Taxon	Native	Functional group	Year 2	Year 3	Year 6
Anemone canadensis (Canada anemone)	Yes	Perennial forb	0.56 (0.03, 1.10)		
Asclepias syriaca (common milkweed)	Yes	Perennial forb		0.76 (0.26, 1.33)	
Elymus trachycaulus (slender wheatgrass)	Yes	Perennial C_3 grass	−0.63 (−1.24, −0.04)		
Heuchera richardsonii (alumroot)	Yes	Perennial forb	0.82 (0.27, 1.41)	0.62 (0.10, 1.20)	
Koeleria macrantha (Junegrass)	Yes	Perennial C_3 grass	−1.23 (−1.97, −0.58)	−0.62 (−1.19, −0.07)	
Lactuca canadensis/ludoviciana (Canada/Louisiana lettuce)	Yes	Annual/biennial/short-lived perennial forb	−0.77 (−1.51, −0.10)		
Linum sulcatum (grooved yellow flax)	Yes	Annual forb	−0.56 (−1.13, −0.05)		
Oenothera biennis (common evening primrose)	Yes	Biennial forb		0.92 (0.30, 1.64)	
Physalis heterophylla/virginiana (clammy/Virginia groundcherry)	Yes	Perennial forb			0.49 (0.03, 0.99)
Solidago nemoralis (gray goldenrod)	Yes	Perennial forb	−0.82 (−1.53, −0.19)		
Medicago lupulina (black medick)	No	Annual/short-lived perennial forb	1.07 (0.36, 1.86)	0.73 (0.01, 1.50)	

TABLE 3 Taxa at Hole in the Mountain that changed in plot occupancy over time in response to grazing and their z-score coefficient estimates (and 95% credible intervals) for interactions between time and grazing (interaction indicated by "×").

TaxaName	Native	Functional group	Year 2 × grazed	Year 5 × grazed
Agrostis gigantea (redtop)	No	Perennial C_3 grass	0.86 (0.02, 1.74)	
Carduus nutans (musk thistle)	No	Biennial forb	1.23 (0.50, 1.97)	0.85 (0.12, 1.6)
Cirsium arvense (Canada thistle)	No	Perennial forb	1.00 (0.25, 1.76)	
Cirsium vulgare (bull thistle)	No	Biennial forb	1.25 (0.48, 2.04)	
Conyza canadensis (horseweed)	No	Annual/biennial forb	1.21 (0.37, 2.07)	
Elymus repens (quackgrass)	No	Perennial C_3 grass	0.75 (0.01, 1.47)	
Medicago lupulina (black medick)	No	Annual/short-lived perennial forb	0.95 (0.20, 1.77)	
Melilotus alba/officinalis (sweetclover)	No	Annual/biennial forb	0.81 (0.11, 1.51)	
Phleum pratense (timothy)	No	Perennial C_3 grass	0.94 (0.09, 1.79)	
Taraxacum officinale (common dandelion)	No	Perennial forb	1.02 (0.21, 1.85)	
Tragopogon dubius (yellow goat's beard)	No	Annual/biennial forb	0.82 (0.09, 1.57)	0.99 (0.29, 1.74)
Trifolium pratense (red clover)	No	Biennial/perennial forb	1.06 (0.29, 1.86)	
Trifolium repens (white clover)	No	Perennial forb	1.18 (0.42, 2.00)	
Ulmus pumila (Siberian elm)	No	Tree	0.89 (0.05, 1.77)	

4 | DISCUSSION

Patch-burn grazing can be an effective management tool for creating habitat heterogeneity for wildlife in the central (e.g., Kansas and Nebraska) and northern (e.g., Dakotas and Minnesota) tallgrass prairie (Fuhlendorf & Engle, 2001; Smart et al., 2016). Yet, the effects of patch-burn grazing on specific components of plant communities are not well understood, particularly in the northern tallgrass prairie where it is less studied

TABLE 4 The effect of grazing on the change in each response variable over time. VOR refers to Visual Obstruction Reading, a measure of vegetation height and density. Mean *C* refers to a frequency-weighted mean coefficient of conservatism, in which *C* values assigned to each species range from 0 (least conservative) to 10 (most conservative).

Site (stocking rate)	VOR	Native spp. richness	Non-native spp. richness	Smooth brome freq.	Mean *C* (natives only)	Mean *C* (natives and non-natives)
Chippewa Prairie (0.8–1.3 AUM/ha)	Decreased in some units in some sampled years	No sig. effect	No sig. effect	No sig. effect	No sig. effect	No sig. effect
Hole in the Mountain (2.2–3.7 AUM/ha)	Decreased in all units each sampled year	No sig. effect	Increased	No sig. effect	No sig. effect	Decreased

Abbreviation: AUM, animal unit months.

(Smart et al., 2016). We used a paired plot study design to compare patch-burn grazing to burning-without-grazing at two dry-mesic prairie sites with different stocking rates. Our study highlights the sensitivity of vegetation structure and non-native plant species richness to patch-burn grazing, as well as the insensitivity of smooth brome frequency and native plant species richness and mean *C* to this management strategy.

The two study sites varied in stocking rate, which may explain some of the differences observed in the results. Hole in the Mountain had a stocking rate of 2.2–3.7 animal unit months (AUM)/ha, which was more than double the rate at Chippewa Prairie, where it was 0.8–1.3 AUM/ha. These rates appear to fall within the range of other patch-burn projects reported in the literature. For example, in tallgrass prairie sites on the same soil types in northeastern South Dakota, stocking rates in the range of 1.3–2.1 AUM/ha were used for patch-burn grazing (Smart et al., 2016). Elsewhere, rates reaching 3 AUM/ha were used for patch-burn grazing in Oklahoma (our calculation) (Fuhlendorf & Engle, 2004) or in rotational grazing at the Broken Kettle Grassland Preserve in Iowa (Brudvig et al., 2007). Determining the appropriate stocking rate would normally depend on the forage production of a site and goals for either livestock production or conservation outcomes for a given year. Managers should frequently evaluate the site and adjust management based on current conditions (e.g., rainfall) and previous years' effects on vegetation composition and structure (Ahlering et al., 2020). This can be a difficult task for those managing multiple sites across different landscapes and weather conditions, and for managers who must arrange grazing in advance with private producers.

Our results suggest that an intermediate stocking rate between those used at both sites (Table 1) may have more effectively achieved a shifting mosaic of vegetation height and density that is a goal of patch-burn grazing (Fuhlendorf & Engle, 2004). At Chippewa Prairie, grazing reduced vegetation structure in only one burn unit the year it was burned. Because the plots were not sampled annually, we have no evidence of the extent of grazing in the years in which units 2 and 3 were burned. Additionally, grazing consistently reduced vegetation structure in unit 1 across years, indicating that livestock preferred this unit. Some trees were present outside the west side of this unit and may have provided some late-day shade. Other studies show that livestock will prefer areas that have woody vegetation or water (Allred et al., 2011). Other than unit 1, the units received less grazing 1–2 years after they were burned than they might have in a more heavily stocked site. On the other hand, the consistent effect of grazing on vegetation structure, regardless of burn timing, at Hole in the Mountain indicated that cattle were utilizing the forage similarly in all three burn units. The relatively small total size of the pasture at Hole in the Mountain (125 ha) may have enabled livestock to travel from one end to the other much more quickly and spend less time focusing on one unit than if they were in a much larger site (Smart et al., 2016). Therefore, this site was likely too overstocked to achieve heterogeneity in vegetation structure. Overgrazing can result in an insufficient spread of fire in a burned unit due to reduced fuel load, thus resulting in less contrast between burned and unburned patches (McGranahan, Engle, Fuhlendorf, et al., 2012). Finding a stocking rate to realize the vegetation structure goals of patch-burn grazing may be generally difficult to achieve. For example, with patch-burn grazing using stocking rates intermediate to Chippewa Prairie and Hole in the Mountain, Smart et al. (2016) found that the most recently burned unit did not have the largest alteration of vegetation structure, though they did find structural heterogeneity in their sites. At the Tallgrass Prairie National Reserve in Kansas, Leis et al. (2013) also found it difficult to create areas of vegetation structure intermediate between well-grazed lawns and ungrazed grassland.

Native plant richness was maintained at Hole in the Mountain and increased over time at Chippewa Prairie. We identified several native species at Chippewa Prairie that contributed to this increase. Nearly all native plants we recorded were long-lived, perennial species, and their frequencies were unlikely to change greatly over periods of 6 or fewer years, though plant species abundances can vary from year to year with variation in precipitation. Patch-burn grazing did not alter native species richness relative to burning-without-grazing at either site, unlike prior studies, where grazing was associated with higher total species richness (Gao & Carmel, 2020; Manning et al., 2017; Symstad & Jonas, 2011) and native species richness (Hickman et al., 2004). We analyzed frequency (presence–absence) instead of foliar cover. The latter may be more sensitive to grazing but represents only temporary responses to grazing (Hartnett et al., 1996). We did not find significant changes in the frequency of dominant warm-season grasses in patch-burn grazing or burning-without-grazing plots at either of the study areas, though warm-season grass cover may have been altered by grazing.

Non-native plant species richness (excluding smooth brome) greatly increased in the more heavily grazed Hole in the Mountain, but not in the more lightly grazed Chippewa Prairie. Nine of the 14 non-native species that significantly increased in Year 2 at Hole in the Mountain were also present but did not significantly increase at Chippewa Prairie. Past land-use history can have a strong effect on community responses to disturbance in northern tallgrass prairie (Coleman et al., 2023). Hole in the Mountain had heavy grazing before its acquisition as a natural area in 1991, and biennial and annual species such as musk thistle, black medick, and white/yellow sweet clover stimulated by grazing at Hole in the Mountain likely had seed present in the seed bank before patch-burn grazing started. Other studies also show a positive association between non-native plant species and cattle grazing (Drew, 1947; Kucera, 1956; McGranahan, Engle, Wilsey, et al., 2012), including light grazing (Brudvig et al., 2007; Grant et al., 2009). We did not see a similar response at Chippewa Prairie, where the stocking rate was much lighter.

Controlling smooth brome is a high management priority in northern tallgrass prairies, as it can be a serious threat to the native plant species composition (Palit & De Keyser, 2022). In Minnesota, abundant roadside plantings of smooth brome and the greater amounts of edge relative to interior space in smaller prairie fragments promote brome invasion (Koper et al., 2010). In addition, smooth brome has a competitive advantage over warm-season grasses when soil nitrogen is elevated, which is caused by atmospheric nitrogen deposition (Wedin & Tilman, 1996) and, especially in recent decades, increased precipitation (Ratcliffe et al., 2024). Finally, smooth brome tends to occur at higher abundances in the northern than central tallgrass prairie (Grant et al., 2009; Smith & Knapp, 1999) potentially due to differences in climate or cultivars (Salesman & Thomsen, 2011). Smooth brome unexpectedly tripled in frequency at Chippewa Prairie over 6 years, but did not significantly increase at the more intensively grazed Hole in the Mountain. Hole in the Mountain had a much higher initial frequency of smooth brome than Chippewa, likely due to the lack of prescribed burning before patch-burn grazing was initiated. At Hole in the Mountain, the high initial frequency created less space within our plots for smooth brome to invade during the study. We did not find a significant effect of grazing on smooth brome frequency within either site, perhaps because frequency underestimates changes in this clonal species relative to a more sensitive metric such as stem density. Smooth brome has a long history of use as a forage species and appears to do well with light grazing (less than 1.8 AUM/ha) (Brudvig et al., 2007; Salesman & Thomsen, 2011). If suppression of a cool-season grass like smooth brome is a priority for managers, then more frequent and focused disturbance would likely be more effective, as found by Willson and Stubbendieck (1997) and Coleman et al. (2023), than the spatially shifting focus of patch-burn grazing. To achieve annual disturbance timed for smooth brome control, alternatives to controlled burns, such as carefully planned livestock grazing or haying, are important tools to consider (Salesman & Thomsen, 2011).

Frequency-weighted mean coefficients of conservatism did not differ between patch-burn grazing and burning-without-grazing treatments at Chippewa Prairie but did at Hole in the Mountain due to an increase of non-native species. When calculated without non-natives, frequency-weighted mean *C* indicated no significant changes in mean conservatism of native species for either study site. Thus, even at the higher stocking rate, patch-burn grazing did not significantly shift the native vegetation from more to less conservative species. These results are similar to those of Larson et al. (2020) where species conservatism (assessed as mean *C* per site) did not differ between 27 grazed-unburned and 46 ungrazed-burned sites in western Minnesota. By contrast, native species conservatism (as measured by Floristic Quality Index per transect) was significantly greater for grazed prairie compared to ungrazed prairie (Coleman et al., 2023; Manning et al., 2017). It should be noted that some of the most conservative plant species, with coefficients of conservatism values of 9 or 10, were absent or highly infrequent in the two study areas before patch-burn grazing began, including compass plant (*Silphium*

laciniatum L.), wood lily (*Lilium philadelphicum* L.), and prairie coreopsis (*Coreopsis palmata* Nutt.) (Minnesota Biological Survey [MBS], 2022). These species are present in small nearby prairie remnants that lacked past intensive pasture management and were most likely eliminated or greatly reduced in the study areas by past land use before the sites were protected for conservation. Thus, generalizations regarding the effects of patch-burn grazing on plant species conservatism in our study are limited by the set of species that were present at the start.

This was the first study of patch-burn grazing in Minnesota, located in the eastern portion of the northern tallgrass prairie. We found that structural heterogeneity was not consistently achieved by either high or low stocking rates on the two study areas. On small sites like those in the eastern tallgrass prairie, managers may need to adjust stocking rates during the season to better achieve site-wide heterogeneity. This may be challenging for managers who must contract in advance with local producers for grazing services. Other adjustments that should be considered include removing attractants that might cause cattle to prefer one burn unit (e.g., sources of shade) or adding attractants (e.g., water) to other burn units to encourage livestock to occupy under-utilized units for a longer period. We found native richness and mean coefficient of conservatism of native plant species present in our two study areas were not affected by grazing at either stocking rate. Our study also demonstrated that several non-native species associated with heavily grazed pastures were stimulated by the grazing at Hole in the Mountain. This study area had last been grazed 27 years earlier, and these species were likely present in the seed bank, confirming other results that suggest the importance of land-use history on management outcomes (Coleman et al., 2023). Managers should be aware of the influence of past land use and potential seed bank composition in planning management strategies. Grazing at a low stocking rate did not cause non-native species to reappear at Chippewa Prairie. Smooth brome was not reduced in either heavily or lightly stocked sites, and alternative management is recommended for smooth brome control in the northern tallgrass prairie.

ACKNOWLEDGMENTS

Initial funding for this project was provided by a grant from the Minnesota Environment and Natural Resources Trust Fund, as recommended by the Legislative-Citizen Committee for Minnesota Resources. Ongoing funding came from the Minnesota Department of Natural Resources Minnesota Game and Fish Fund. This project would not have been possible without the support and energy of C. Converse and B. Carlson; or the collaboration of D. Trauba, P. Baumann, J. Blastick, A. Knutson and M. Benage. D. Larson, M. Ahlering and D. Buhl helped design a study plan for this project. We are indebted to several botanists who sampled the plots: P. Bockenstedt, J. Flory, B. Hoksch, J. Larson, M. Lynch, S. Nelson, W. Norris, S. Simmers, L. Toso and S. Zager. Review comments from M. Ahlering, H. Bernardo, D. Larson, and J. Petersen greatly improved the manuscript. Comments from three anonymous reviewers substantially improved the manuscript.

DATA AVAILABILITY STATEMENT

Data and code are available on the Environmental Data Initiative Portal: https://doi.org/10.6073/pasta/cca4006a90590659349bac821748a7be.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Harris, F. S., Graham, D. R. J., & Kendig, A. E. (2025). Comparing the impacts of patch-burn grazing on vegetation in two northern tallgrass prairies. *Conservation Science and Practice*, *7*(10), e70128. https://doi.org/10.1111/csp2.70128