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Effective Management Practices for Increasing Native Plant Diversity on Mesquite Savanna-Texas Wintergrass-Dominated Rangelands☆

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ABSTRACT

Throughout the Rolling Plains and Cross Timbers ecoregions of Texas, native grassland plant communities have been converted into low-diversity plant communities by long-term, intensive overgrazing by cattle and fire suppression. Much of the historical plant community has become dominated by annuals, Texas wintergrass *(Nassella leucotricha)*, and honey mesquite *(Prosopis glandulosa)*. This degradation has been so severe that many native bird species, including Northern bobwhite *(Colinus virginianus)*, have experienced drastic population declines. We conducted a small-plot study to determine effective management actions for transforming mesquite savanna—Texas wintergrass communities to diverse native plant communities supportive of native wildlife species. We tested multiple management practices following mechanical mesquite brush removal, including seeding, timed treatments of herbicide, prescribed burns, and high-intensity, short-duration cattle grazing. Results indicated that plots receiving early spring treatments of herbicide followed by burning and grazing over 2 consecutive yr best reduced cool-season grasses and promoted overall restoration goals by increasing native warm-season grass and forb establishment.

Introduction

Many grassland bird populations are threatened by the conversion of their original native grassland habitat to degraded rangelands. Northern bobwhite *(Colinus virginianus)*, Sprague's pipit *(Anthus spragueiie)*, loggerhead shrike *(Lanius ludovicianus)*, northern harrier *(Circus cyaneus)*, eastern meadowlark *(Sturnella magna)*, dickcissel *(Spiza Americana)*, grasshopper sparrow *(Ammodramus savannarum)*, sedge wren *(Cistothorus platensis)*, Le Conte's sparrow *(Ammodramus leconteii)*, and the field sparrow *(Spizella Americana)* are some of the species of concern (Texas Parks and Wildlife Department 2012; Sauer et al. 2017). The fundamental problem for these bird species is loss of plant communities with greater structural and species diversity for which they are adapted (Fuhlendorf et al. 2006; Ransom Jr. and Schulz 2007; Reynolds and Symes 2013). Decades of continuous intensive overgrazing by cattle and fire suppression has caused much of this loss of habitat (Renwald et al. 1978; Brown 1982; Campbell-Kissock et al. 1984; Ransom Jr. and Schulz 2007).

Historically, there was a high level of structural and species diversity within the native grassland communities of the southern Great Plains (Dyksterhius 1948; Ratajczak et al. 2012). Differences in growth characteristics of grasses, such as rhizomatous, stoloniferous, or bunch, within these native plant communities and a variety of grass and forb heights in association with species richness contributed to habitat diversity capable of fulfilling the annual habitat requirements of this grassland avian community (Fuhlendorf and Engle 2001). Because of fire suppression and intensive continuous grazing by cattle, many of these plant communities transitioned from tallgrass-midgrass rangeland to species-poor midgrass-shortgrass-mesquite *(Prosopis glandulosa)* rangeland (Teague et al. 2009). These converted rangelands are characterized by increased mesquite cover, reduced warm-season forbs and grasses, and increased dominance of cool-season grasses, including Texas wintergrass *(Nassella leucotricha)* and brome (*Bromus* spp.) (Soil Survey Staff 2019).

Cool season grasses, such as Texas wintergrass and brome, dominate many current plant communities in the Rolling Plains and

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Cross Timbers Ecoregions associated with woody vegetation encroachment. Texas wintergrass, a cool-season perennial that was historically a minor component of these regions, is now the dominant perennial grass associated with mesquite encroachment (Dyksterhius 1948). The shaded undercanopy microenvironment of mesquite cover favors C3 cool-season grasses over historically dominant perennial C4 warm-season grasses (Ansley et al. 2013). Decreases in perennial C4 mid and tall grasses likely relate to peak productivity coinciding with full mesquite canopy cover occurring in the warm season (Ansley et al. 1992). Increasing mesquite canopy cover limits light to C4 grasses during their growing season, while providing appropriate microclimate for Texas wintergrass. In the cool season, when deciduous mesquite has no foliage, Texas wintergrass grows unhindered by canopy shading (Simmons et al. 2008; Teague et al. 2014). Change from C4 perennial grasses to C3 species across the landscape is directly related to increasing canopy cover of mesquite (Ansley et al. 2013). Cool season annual grasses, such as brome, also thrive in these disturbed rangelands. These cool-season grasses compete for resources, especially affecting warm-season forb and grass establishment in the spring (Ashton et al. 2016).

The first step to transitioning mesquite savanna–Texas wintergrass communities back to warm-season grasslands is removal of the mesquite canopy. Commonly used methods include bulldozing, grubbing, and herbicide. Along with brush removal, the Natural Resource Conservation Service (Soil Survey Staff 2019) recommends seeding diverse herbaceous species, prescribed fire, and prescribed grazing as possible land management tools to restore these areas. Simply removing mesquite trees often does not result in restoration of the herbaceous community back to diverse grasslands. Depending on the length of time since woody encroachment, change back to the pre-encroachment native herbaceous community may be difficult (Ansley et al. 2013). Once cool-season species become well established, they can maintain an advantage by monopolizing resources, even after mesquite trees are removed; management actions to shift competition advantages back to diverse, warm-season native herbaceous species are often needed (Ansley et al. 2019).

Grassland seeding success is often dependent on site preparation for reducing competition and improving growing conditions (Farthing et al. 2018). Herbicides have been used in restoration to free resources through targeted removal of species (Kyser et al. 2013). Prescribed fire can also modify community structure by changing aboveground plant biomass, species composition, structure, and microclimate (Howe 2000; Brockway et al. 2002). Like fire, grazing can either promote or inhibit growth of plants depending on timing and intensity (Byrnes et al. 2018).

Our goal in this study was to develop best management practices that restore mesquite-Texas wintergrass-dominated areas to diversified native warm-season perennial grasslands, resulting in better habitat for native grassland birds, specifically northern bobwhite quail. This 4-yr study used combinations of herbicide, fire, and high-intensity, short-duration grazing (15 000–20 000 kg cattle ha^{-1}) in conjunction with seeding to determine the most effective restoration practices to be conveyed to landowners and land managers. Findings could guide future conversion of mesquite savanna-Texas wintergrass-dominated communities within the Rolling Plains and Cross Timbers Ecoregions of Texas, as well as other mesquite-invaded areas. We have outlined the objectives as follows:

Objective 1: Determine if cool-season application of glyphosate, prescribed fire, or high-intensity, short-duration grazing alone or in combination as single-yr treatments or sequentially over 2 yr reduces percent cover of Texas wintergrass and brome compared with a control.

Objective 2: Determine the percent cover of seeded native grasses and forbs following the treatments listed in Objective 1.

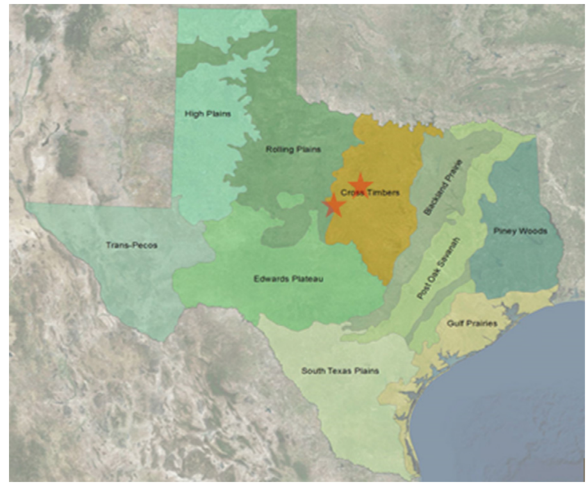

Figure 1. Study site locations.

Methods

Study Location

Study sites were selected based on even distribution of mesquite and a high percent cover of Texas wintergrass. Site 1 (32.215125 N, −98.102417 W; Fig. 1) is located at Hunewell Ranch, a Tarleton State University–owned property in Stephenville, Texas. Stephenville is within Erath County in the Cross Timbers Ecoregion of Texas. Hunewell was moderately to heavily grazed by cattle until study initiation. Site 2 (31.891006 N, −98.835990 W) is located at McGillivray and Leona McKie Muse WMA, a Texas Parks and Wildlife Department (TPWD)–owned property located in Brown County within the Cross Timbers Ecoregion of Texas. Muse was without cattle for 8 yr before the study and was moderately to heavily grazed before cattle removal. As a result, Texas wintergrass cover was higher at Muse (72.5 ± 3.9 SE) than Hunewell (31.9 ± 3.7 SE) before beginning the study. Recent grazing disturbance at Hunewell also resulted in higher percent bare ground and ruderal species, such as western ragweed *(Ambrosia psilostachya)* and brome. Both sites were considered Claypan Prairie ecological sites (Soil Survey Staff 2019). Soil at Hunewell, based on six randomly placed 15-cm cores, was a sandy loam with pH 6.1, nitrogen 2.5 ppm, phosphorus 12.7 ppm, and organic matter 1.2%. Soil at Muse was a clay loam with pH 6.4, nitrogen 3.7 ppm, phosphorus 11.6 ppm, and organic matter 3.5%. Monthly precipitation data for the length of the study was partitioned into winter (December, January, February); spring (March, April, May); summer (June, July, August); and fall (September, October, November) (National Climatic Data Center) (Fig. 2).

Site Preparation

Mesquite Removal and Seeding

All mesquite trees were mechanically removed by a bulldozer from each site in March 2015, with emphasis on minimizing soil disturbance. A bulldozer was used because it is a common method used by landowners to remove mesquite. At Hunewell, mesquite cover was 32% with a density of 466 trees/ha. At Muse, mesquite cover was 61% with a density of 380 trees/ha. Both sites had similar average mesquite basal diameters (12 cm) and heights (3 m); however, Hunewell had more multistem trees with an average number of stems of 2.2 versus 1.8 for Muse. Following mesquite removal, six 40×55 m (2 200 m^2) treatment plots were created at each site. A Truax no-till seed drill was used to plant native grasses and forbs at a seeding rate of approximately 269 seeds/m^2

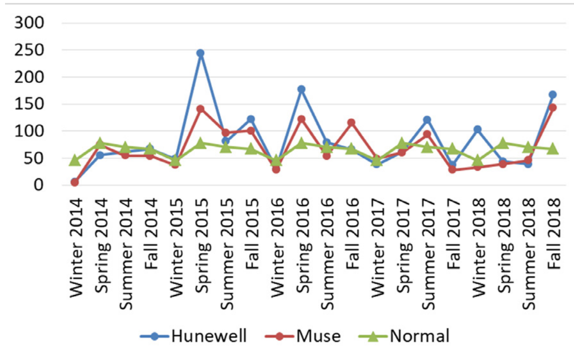

Figure 2. Rolling 3-mo average precipitation data for the study period 2014–2018 for both locations.

Table 1
Treatments applied to 10 × 10 m subplots. Yr 1 indicates first-yr treatments, applied in 2016. Yr 2 indicates second-yr treatments, applied in 2017.

Treatment	Treatment description
H1	Herbicide applied in Yr 1
H2	Herbicide applied in 2 consecutive yr: Yr 1 & 2
B1	Burning applied in Yr 1
G2	Grazing applied in 2 consecutive yr: Yr 1 & 2
C	Control: no treatments applied
H1B1	Herbicide applied in Yr 1 followed by burning in Yr 1
H1B1G2	Herbicide, burning, and grazing applied sequentially in Yr 1, with grazing repeated in Yr 2
H2B2	Herbicide followed by burning for 2 consecutive yr: Yr 1 & 2
H2B2G2	Herbicide, burning, and grazing applied sequentially for 2 consecutive yr: Yr 1 & 2
B1G2	Burning Yr 1 followed by grazing 2 consecutive yr: Yr 1 & 2

within three of six study plots in early April 2015. The seeded plots were chosen randomly from the six total plots at each site. Seed was purchased from Turner Seed Co. in Breckenridge, Texas. The seeding mix was determined from consultation with TPWD staff for favorable quail habitat and was based on the historical reference community determined from NRCS ecological site descriptions for each study site (Soil Survey Staff 2019). The seed mixture included, by seed weight, 28% sideoats gramma *(Bouteloua curtipendula)*, 8% little bluestem *(Schizachyrium scoparium)*, 5% Indiangrass *(Sorghastrum nutans)*, 6% Blackwell switchgrass *(Panicum virgatum)*, 5% buffalo grass *(Buchloe dactyloides)*, 8% Arizona cottontop *(Digitaria californica)*, 5% blue grama *(Bouteloua gracilis)*, 8% tall dropseed *(Sporobolus compositus)*, 5% purple threeawn *(Aristida purpurea)*, and 5% western wheatgrass *(Pascopyrum smithii)*, while forb species included 2% Engelman daisy *(Engelmannia peristenia)*, 4% Illinois bundleflower *(Desmanthus illinoensis)*, 4% partridge pea *(Chamaecrista fasciculata)*, 4% Maxmillian sunflower *(Helianthus maximiliani)*, 2% purple prairie clover *(Dalea purpurea)*, and 2% greenthread *(Thelesperma filifolium)*.

Plot Layout

We subdivided each 40 × 55 m treatment plot, seeded and unseeded, into twelve 10 × 10 m (100 m^2) subplots, each separated by a 5-m buffer zone. Within the subplots, herbicide application, prescribed burning, and grazing treatments were applied individually and in combination in a strip-plot design. In total, 10 different treatments or combinations, including control, were applied (Table 1).

Treatments

Herbicide

Subplots scheduled for herbicide application received treatment with glyphosate (Roundup PowerMax—48% active ingredients) in mid-March 2016 (treatment Yr 1) with a CO_2 pressured backpack sprayer with boom using a metronome to ensure a consistent application rate. Glyphosate (2-phosphonomethylamino acetic acid) is a nonselective, contact herbicide (EPA 1993; Kelly 2005). The application was timed with growing season of the cool-season target species, while nontarget warm-season species were dormant. Glyphosate was applied at 2 L/ha with an application rate equivalent to 4 L product/ha (1.7 qt/acre). Subplots scheduled for a single herbicide treatment (H1) were not retreated in treatment Yr 2. Subplots scheduled for a second herbicide treatment (H2) received a second application of glyphosate in treatment Yr 2 according to the above protocol in mid-March 2017.

Fire

Half the herbicide and grazed subplots at both locations were burned (B) in late March 2016, treatment Yr 1. The prescribed burn was uniform to nearly uniform in subplots receiving the herbicide treatment and patchy in nonherbicide areas. Fuel loading was measured with clipped quadrats approximately 1 wk before the burn; Muse had 1 929 kg/ha (1 722 lb/acre) dry biomass and Hunewell had 2 335 kg/ha (2 085 lb/acre). A second fire treatment was applied early April 2017 on subplots having herbicide (H2B2) applied in treatment Yr 2. These subplots were burned approximately 14 d following herbicide application. Fire was only applied to subplots receiving herbicide in treatment Yr 2 due to the patchy nature of burning in green (nonherbicide) subplots noted from the treatment Yr 1 burn.

Grazing

Grazing was applied as a treatment in early May, treatment Yr 1, within half the herbicide and burn subplots. Each site was grazed 6 d with 8 mature cows (≈545 kg each). The area enclosed for grazing was approximately 8 000 m^2 (0.8 ha) including buffers. The grazing rate expressed as number of head/ha/d was 1.7 cows/ha/d. Grazing appeared to be uniform across the site. From pregrazing and postgrazing measurements of clipped quadrats, as measured in otherwise untreated areas (controls), we measured a 67% decrease in herbaceous aboveground biomass dry weight at Muse and a 65% decrease in biomass dry weight at Hunewell. The grazing treatments were repeated in treatment Yr 2 at both sites. Grazing was done in mid-April to early May for a minimum of 6 d at each site, resulting in a 77% decrease of biomass dry weight at Hunewell and 49% at Muse.

Vegetation Monitoring

Quadrats

Permanent vegetation transects were established within each subplot. Along each transect, 5 Daubenmire (Daubenmire 1959) quadrats (0.25 m^2) were evaluated within each treatment subplot every fall (October–November) and spring (February–April) beginning in fall 2015 (pretreatment) until fall 2018. This allowed 15 quadrats (5 quadrats × 3 subplots) to be sampled per treatment at each site per season. Data for each site were organized by sampling season. Percent cover was categorized into functional groups (Fuhlendorf and Engle 2004): Texas wintergrass, brome, seeded native perennial grasses, and seeded native perennial forbs.

Data Analyses

Analysis of variance was performed to determine treatment effect on percent cover of Texas wintergrass, brome, seeded native perennial grasses, and seeded native perennial forbs. The dependent variables measured were Daubenmire cover class midpoints for percent cover of the functional groups averaged across the five quadrats read in each treatment subplot so that each treatment subplot was considered the sampling unit. Each site had three

Table 2
Mean percent cover of Texas wintergrass (± standard of error) across treatments and sampling seasons.

	Spring 2016: pretreatment		Spring 2017: one growing season post Yr 1 treatments		Spring 2018: one growing season post Yr 2 treatments	
	Hunewell	Muse	Hunewell	Muse	Hunewell	Muse
C	20.9 ± 8.6Aa[1]	36.8 ± 3.7Aa	7.0 ± 2.9Aa	46.1 ± 7.4Ca	11.2 ± 4.9Aa	58.5 ± 9.7Ca
H2	20.4 ± 6.8Aa	32.8 ± 2.8Aa	(5.4 ± 2.4)Aa	(18.5 ± 2.8)ABb	6.6 ± 3.1Aa	9.9 ± 3.6Ab
H1	8.1 ± 3.1Aa	39.9 ± 7.8Aa	3.1 ± 1.4Aa	12.9 ± 2.3Aa	7.1 ± 4.7Aa	28.3 ± 7.3ABCa
B1	12.2 ± 4.3Aa	26.9 ± 5.6Aa	10.2 ± 4.3Aa	43.4 ± 8.9Cda	8.2 ± 3.2Aba	34.2 ± 8.2ABCa
H2B2	11.6 ± 5.2Aa	35.0 ± 4.5Aa	(3.8 ± 1.1)Aa	(18.0 ± 3.9)ABab	4.7 ± 2.8Aa	7.6 ± 2.7Ab
H1B1	15.8 ± 5.1Aa	36.3 ± 8.2Aa	4.1 ± 1.4 Aa	15.2 ± 4.9Aa	6.5 ± 3.2Aba	32.1 ± 7.4ABCa
B1G2	10.3 ± 2.1Aa	27.9 ± 7.3Aa	(10.1 ± 2.7)Aa	(35.2 ± 7.9)ABCa	22.2 ± 4.7Ba	46.4 ± 9.3Bca
H2B2G2	12.2 ± 4.3Aa	34.4 ± 6.3Aa	(6.3 ± 2.0)Ab	(13.9 ± 1.8)Ab	4.4 ± 2.1Ab	11.5 ± 3.3Ab
H1B1G2	15.5 ± 6.0Aa	39.4 ± 7.8Aa	(3.1 ± 1.4)Aa	(12.2 ± 2.5Ab	12.8 ± 4.3ABa	24.9 ± 7.1Abab
G2	10.8 ± 2.2Aa	27.4 ± 2.8Aa	(8.2 ± 1.4)Aa	30.7 ± 4.0ABCa	15.0 ± 2.4ABa	37.9 ± 5.2ABCa

C indicates control; H1, herbicide applied once; H2, herbicide applied twice; B1, burned once; G2, grazed twice.
[1] Values in columns followed by different uppercase letters and in rows followed by different lowercase letters differed according to pairwise comparisons with Tukey's honestly significant difference test ($P \leq 0.05$).

replicate sampling units. We used analysis of variance to compare mean percent cover of dependent variables (functional groups) for multiple individual treatments or treatment combinations. Individual and combinations of treatments (independent variables) for the analysis included control (C), herbicide × 1 (H1), herbicide × 2 (H2), burn × 1 (B1), herbicide × 2-burn × 2 (H2B2), herbicide × 1-burn × 1 (H1B1), burn × 1-graze × 2 (B1G2), herbicide × 2-burn × 2-graze × 2 (H2B2G2), herbicide × 1-burn × 1-graze × 2 (H1B1G2), and graze × 2 (G2). Because site differences existed based on preliminary Texas winter grass percent cover ($t [10] = 7.5$, $P \leq 0.05$), each location was treated as a separate experiment. Both 1-way analysis of variance (ANOVA), to detect same-year differences across treatments, and repeated measures ANOVA, to detect same-treatment differences across multiple years of sampling, were performed. When there were significant differences among mean percent cover, we performed multiple comparison post hoc analysis with Tukey's honestly significant difference test to determine if different mean percent cover existed among treatments with a 95% confidence level. Differences were considered significant at $P \leq 0.05$.

Overall Treatment Ranking

Results of treatments considered favorable to restoration of mesquite-Texas wintergrass–invaded grasslands included those resulting in reductions in Texas wintergrass cover, reductions in cool-season annual grass cover (brome), and increases in seeded perennial grasses and forbs. Analysis was done as a percent change in cover values from pretreatment to the final survey dates in 2018 for each of the four variables: Texas wintergrass decrease, brome decrease, seeded grass increase, and seeded forb increase. This represented a percent change in cover over time from pretreatment to one growing season post Yr 2 treatments. Because brome and seeded forbs were virtually absent from Muse, they were not included in this analysis. Percent change values were then ranked by treatment from 1 to 10 according to whether the desired change was to increase or decrease. The rankings for each variable were then averaged for each site and across both sites to give an "equal weight" indication of which treatments were most successful.

Results

Reduction of Texas Wintergrass

Percent cover of Texas wintergrass in spring 2016 (pretreatment) did not differ among treatment plots at either site (Table 2). For Texas wintergrass, a cool-season perennial, one growing season post-treatment Yr 1 (spring 2017), herbicide × 1 treatments (H1 and H1B1) showed lower Texas wintergrass percent cover than controls within same-year comparisons at Muse. Since Yr 2 treatments had not been performed yet, H2, H2B2, H2B2G2, H1B1G2, and G2 treatments were not considered for analysis for spring 2017 data. By one growing season post-treatment Yr 2 (spring 2018) at Muse, only herbicide × 2 treatments (H2, H2B2, and H2B2G2) showed lower Texas wintergrass cover than control. Herbicide × 1 treatments were no longer reduced, with the exception of H1B1G2, which involved a combination of all suppression treatments. At Hunewell, B1G2 had higher percent cover than C, H2, H1, B1, H2B2, H1B1, and H2B2G2. At Hunewell, same-treatment comparisons across multiple sampling seasons indicated no differences. At Muse, H2, H2B2, H2B2G2, and H1B1G2 treatments reduced Texas wintergrass cover between 2016 and 2018.

Reduction of Brome

Brome is a cool-season annual grass that benefits from disturbance (Whisenant and Uresk 1990). Following disturbance from mesquite removal at Hunewell, brome became prominent. For percent cover of brome, same-year comparisons were performed for only Hunewell because Muse had overall very low percent brome cover (Table 3). For spring 2016 (pretreatment) there were no differences among treatments. Herbicide × 1 treatment followed by burning (H1B1), herbicide × 1 (H1), and burn × 1 (B1) showed lower percent cover of brome than control one growing season post-treatment Yr 1 (2016). By 2017, herbicide × 1 (H1) and G2 were higher in brome cover than control, from growth by seed since it is an annual. Same-treatment comparisons across multiple sampling seasons indicated an increase in percent cover in the control plots between 2016 and 2017. In treatment H1B1 subplot, brome cover increased from 2017 to 2018. In treatment H2B2G2, brome cover decreased sequentially from 2016 to 2017 to 2018.

Overall Seeded Species

Analysis of all seeded plots, regardless of treatment, indicated differences in percent cover of seeded species among sample years (Table 4). Both Hunewell and Muse percent cover of seeded species increased through time and differed between fall 2015 (one growing season post seeding) and fall 2017 (three growing seasons post seeding).

Seeded Native Grasses

In fall 2015 (pretreatment) there were no differences in percent cover of seeded grasses among treatments (Table 5). For fall 2016 (one growing season post-treatment Yr 1) at Hunewell, seeded native perennial grass cover of H1B was higher than C. At Muse, H1

Table 3
Mean percent cover of brome (± standard of error) across treatments and sampling seasons.

	Spring 2016: pretreatment		Spring 2017: one growing season post Yr 1 treatments		Spring 2018: one growing season post Yr 2 treatments	
	Hunewell	Muse	Hunewell	Muse	Hunewell	Muse
C	22.4 ± 3.6 Aa[1]	0.4 ± 0.2	56.3 ± 5.7 Db	7.9 ± 4.1	26.4 ± 6.9 Aba	0.8 ± 0.6
H2	20.2 ± 2.5 Aa	1.4 ± 1.3	(23.7 ± 3.6) ABCa	(0.7 ± 0.6)	21.6 ± 6.8 Aba	0.1 ± 0.1
H1	28.6 ± 9.6 Aa	1.0 ± 0.7	32.9 ± 8.1 Cda	0.2 ± 0.1	39.6 ± 7.6 Ba	0.0 ± 0.0
B1	32.2 ± 12.2 Aa	0.4 ± 0.2	37.2 ± 6.7 Cda	7.2 ± 7.1	25.0 ± 7.3 Aba	0.1 ± 0.1
H2B2	24.6 ± 7.2 Aa	1.2 ± 1.1	(7.4 ± 6.3)ABa	(0.6 ± 0.6)	8.5 ± 6.8 Aa	0.0 ± 0.0
H1B1	16.0 ± 5.4 Aab	0.4 ± 0.2	3.2 ± 1.3 Aa	0.0 ± 0.0	14.6 ± 2.7 Ab	0.0 ± 0.0
B1G2	24.8 ± 9.1 Aa	0.3 ± 0.1	(30.9 ± 9.8) BCDa	(0.2 ± 0.1)	13.5 ± 3.4 Aa	0.2 ± 0.1
H2B2G2	27.5 ± 4.4 Aa	0.0 ± 0.0	(3.3 ± 0.6)Ab	(0.0 ± 0.0)	4.2 ± 1.8 Ab	0.0 ± 0.0
H1B1G2	13.0 ± 3.5 Aa	0.5 ± 0.3	(1.4 ± 0.5)Aa	(0.0 ± 0.0)	10.8 ± 4.0 Aa	0.0 ± 0.0
G2	26.9 ± 5.0 Aa	0.4 ± 0.2	(40.1 ± 3.4) CDa	(0.1 ± 0.0)	19.8 ± 2.5 ABa	0.0 ± 0.0

C indicates control; H1, herbicide applied once; H2, herbicide applied twice; B1, burned once; G2, grazed twice.
[1] Values in columns followed by different uppercase letters and in rows followed by different lowercase letters differed according to pairwise comparisons with Tukey's honestly significant difference test ($P \leq 0.05$).

Table 4
Mean percent cover of seeded species (± standard of error).

	Hunewell	Muse
Fall 2015	4.8 ± 0.9A[1]	2.5 ± 0.4A
Fall 2016	6.6 ± 1.2A	4.3 ± 0.7AB
Fall 2017	11.8 ± 1.9B	6.6 ± .3B
Fall 2018	13.3 ± 1.9B	12.0 ± 1.9C

[1] Values in columns followed by different uppercase letters differed according to pairwise comparisons with Tukey's honestly significant difference test ($P \leq 0.05$).

and B1 were higher than C. Because Yr 2 treatments had not been performed yet, H2, H2B2, H2B2G2, H1B1G2, and G2 treatments were not considered for analysis of fall 2016 data. For fall 2017 (one growing season post-treatment Yr 2) no differences existed among treatments at either site. For fall 2018 (two growing seasons post-treatment Yr 2) no differences existed among treatment seeded native perennial grass cover at either site. Same-treatment comparisons across multiple sampling seasons indicated no differences at either site.

Seeded Native Forbs

Percent cover of seeded forbs in fall 2015 (pretreatment) at Hunewell did not differ among treatment plots (Table 6). At Muse, B1G2 was higher than all other treatments. For fall 2016 (one growing season post-treatment Yr 1), no differences existed among treatments at either site. Overall cover of seeded perennial forbs was generally lower at Muse than at Hunewell. Since second-yr treatments had not been performed yet, H2, H2B2, H2B2G2, H1B1G2, and G2 treatments were not considered for analysis of fall 2016 data. For fall 2017 (one growing season post-treatment Yr 2), no differences existed among treatments at either site. At Muse, overall percent cover of seeded perennial forbs was low. For fall 2018 (two growing seasons post-treatment Yr 2), at Hunewell, no differences existed among treatments. At Muse, seeded native perennial forb cover for B1G2 was higher than all other treatments. Same-treatment comparisons across multiple sampling seasons indicated no differences.

Overall Treatment Ranking

Treatments resulting in the greatest reduction of cool-season grasses and greatest increase in native seeded grasses and forbs were ranked 1−10 per site and averaged across the two sites (Table 7). At Hunewell, treatments ranked in order of most successful to least successful were H2B2G2, H2, C, H2B2, B1, H1B1, G2, H1B1G2, B1G2, and H1. At Muse, treatments ranked H2B2G2, H2B2, H1, H2, H1B1, B1G2, H1B1G2, G2, B1, and C. Averaged across both sites, treatments ranked H2B2G2, H2B2, H2, H1B1, H1, B1, C, G2, B1, G2, B1G2, and H1B1G2.

Discussion

Reduction of Cool Season Grasses

Across both sites, based on ranking, the three most successful treatments at reducing cool-season grasses included herbicide applied consecutively over two cool seasons, as an independent treatment (H2) or in combination with burning (H2B2) or burning and grazing (H2B2G2). However, differences existed among sites, target

Table 5
Mean percent cover of seeded native grasses (± standard of error) across treatments and sampling seasons.

	Fall 2015: pretreatment		Fall 2016: one growing season post yr 1 treatments		Fall 2017: one growing season post yr 2 treatments		Fall 2018: two growing seasons post Yr 2 treatments	
	Hunewell	Muse	Hunewell	Muse	Hunewell	Muse	Hunewell	Muse
C	2.2 ± 0.9Aa[1]	3.7 ± 1.3Aa	4.8 ± 3.5Aa	6.3 ± 2.8Aa	10 ± 7.4Aa	13.7 ± 6.5Aa	25.7 ± 5.7Aa	9.7 ± 5.1Aa
H2	3.3 ± 1.2Aa	4 ± 1.6Aa	(14.8 ± 5.0)Aa	(10.2 ± 5.4)Aa	30.8 ± 12.5Aa	20.2 ± 15.2Aa	27 ± 12.3Aa	18.2 ± 9.0Aa
H1	5.7 ± 4.2Aa	1.2 ± 0.7Aa	8 ± 2.3Aa	12.5 ± 8.7Aa	12.3 ± 3.0Aa	12.3 ± 10.6Aa	29.7 ± 7.3Aa	12.0 ± 4.0Aa
B1	7.7 ± 4.3Aa	6.3 ± 2.9Aa	6.8 ± 1.7Aa	11.8 ± 4.4Aa	6.3 ± 1.4Aa	16.5 ± 6.5Aa	12.2 ± 5.3Aa	19.0 ± 7.5Aa
H2B2	8.2 ± 3.2Aa	3.7 ± 1.5Aa	(15.2 ± 3.7)Aa	(8.2 ± 2.8)Aa	28.5 ± 4.8Aa	19.7 ± 10.2Aa	29.7 ± 13.4Aa	21.8 ± 7.4Aa
H1B1	11 ± 8.3Aa	2.5 ± 1.1Aa	15.3 ± 5.7Aa	4.7 ± 1.6Aa	15.7 ± 9.2Aa	15.5 ± 6.1Aa	16 ± 10.8Aa	17.8 ± 7.4Aa
B1G2	9.2 ± 5.2Aa	2.8 ± 0.7Aa	(11 ± 9.1)Aa	(5.8 ± 1.8)Aa	26.8 ± 11.6Aa	16.5 ± 9.7Aa	15 ± 9.2Aa	20.8 ± 8.8Aa
H2B2G2	5.2 ± 2.8Aa	1.3 ± 0.4Aa	(9.2 ± 1.3)Aa	(5.8 ± 2.6)Aa	18.7 ± 8.4Aa	11.5 ± 4.4Aa	23 ± 10.1Aa	14.8 ± 3.0Aa
H1B1G2	5.3 ± 2.0Aa	2.8 ± 1.1Aa	(14.7 ± 6.6)Aa	(6.3 ± 1.2)Aa	13 ± 4.9Aa	9.2 ± 7.9Aa	22.8 ± 14.1Aa	7.0 ± 3.9Aa
G2	5.5 ± 4.2Aa	2.3 ± 0.5Aa	(6.9 ± 2.3)Aa	(7.8 ± 1.7)Aa	15.5 ± 8.2Aa	6.2 ± 2.3Aa	12.2 ± 4.4Aa	11.0 ± 6.0Aa

C indicates control; H1, herbicide applied once; H2, herbicide applied twice; B1, burned once; G2, grazed twice.
[1] Values in columns followed by different uppercase letters and in rows followed by different lowercase letters differed according to pairwise comparisons with Tukey's HSD ($P \leq 0.05$).

Table 6
Mean percent cover of seeded native forbs (± standard of error) across treatments and sampling seasons.

	Fall 2015: pretreatment		Fall 2016: one growing season post yr 1 treatments		Fall 2017: one growing season post yr 2 treatments		Fall 2018: two growing seasons post yr 2 treatments	
	Hunewell	Muse	Hunewell	Muse	Hunewell	Muse	Hunewell	Muse
C	1.3 ± 1.1Aa[1]	0.3 ± 0.2Aa	0.2 ± 0.2Aa	0.2 ± 0.2Aa	1 ± 1.7Aa	0 ± 0.0Aa	5.5 ± 2.5Aa	0 ± 0.0Aa
H2	2 ± 2.0Aa	0 ± 0.0Aa	(3 ± 2.3)Aa	(0 ± 0.0)Aa	12.7 ± 5.1Aa	0 ± 0.0Aa	3.8 ± 3.4Aa	0 ± 0.0Aa
H1	1 ± 1.0Aa	0 ± 0.0Aa	0.3 ± 0.2Aa	0 ± 0.0Aa	2.7 ± 2.5Aa	0 ± 0.0Aa	0 ± 0.0Aa	0 ± 0.0Aa
B1	1 ± 1.0Aa	0.5 ± 0.3Aa	0.3 ± 0.4Aa	0 ± 0.0Aa	8.2 ± 6.8Aa	0.3 ± 0.3Aa	3.3 ± 2.8Aa	0 ± 0.0Aa
H2B2	3.8 ± 2.4Aa	0.2 ± 0.2Aa	(8.5 ± 4.4)Aa	(0.5 ± 0.0)Aa	12.2 ± 4.0Aa	0 ± 0.0Aa	1.2 ± 0.9Aa	0 ± 0.0Aa
H1B1	4.7 ± 4.5Aa	0.7 ± 0.2Aa	7.3 ± 6.0Aa	0 ± 0.0Aa	7 ± 7.1Aa	0 ± 0.0Aa	5.7 ± 3.1Aa	0 ± 0.0Aa
B1G2	3.2 ± 1.8Aa	1.2 ± 0.5Ba	(1.3 ± 1.1)Aa	(0 ± 0.0)Aa	1.2 ± 1.2Aa	0 ± 0.0Aa	1 ± 1.0Aa	0.7 ± 0.2Ba
H2B2G2	3 ± 1.8Aa	0.5 ± 0.3Aa	(9.8 ± 5.4)Aa	(0 ± 0.0)Aa	11.3 ± 9.5Aa	0 ± 0.0Aa	5.7 ± 5.0Aa	0.2 ± 0.2Aa
H1B1G2	3.3 ± 1.5Aa	0.7 ± 0.4Aa	(2 ± 0.5)Aa	(0.2 ± 0.2)Aa	1 ± 1.0Aa	0.2 ± 0.2Aa	1 ± 1.0Aa	0 ± 0.0Aa
G2	2.3 ± 1.0Aa	0.3 ± 0.2Aa	(1.1 ± 0.2)Aa	(1.3 ± 0.8)Aa	1.9 ± 0.8Aa	0.1 ± 0.1Aa	2.4 ± 2.0Aa	0 ± 0.0Aa

C indicates control; H1, herbicide applied once; H2, herbicide applied twice; B1, burned once; G2, grazed twice.
[1] Values in columns followed by different uppercase letters and in rows followed by different lowercase letters differed according to pairwise comparisons with Tukey's honestly significant difference test ($P \leq 0.05$).

species (Texas wintergrass vs. brome), and treatments. Treatments H2B2G2, H2B2, and H2 reduced Texas wintergrass as compared with same-year controls and ranked as the top three treatments for Texas wintergrass suppression at both sites. For brome, H2B2G2 decreased cover across multiple years and ranked number 1 for brome suppression, just above H2B2. Treatment H2 ranked very low (8) for brome suppression. Likewise, herbicide applied once (H1) did not result in sustained suppression of cool-season grasses. Treatment H1 ranked 8 at Hunewell and 5 at Muse for Texas wintergrass and 10 for brome at Hunewell. Herbicide × 1 treatments initially reduced Texas wintergrass and brome, but cover was reestablished by 2-3 years post Yr-1 treatments. A second yr of herbicide was needed to more thoroughly suppress regrowth of perennial Texas wintergrass and growth of annual brome from seed.

Burning, with or without grazing, contributed to cool-season grass mortality beyond herbicide alone and led to a reduction in cool-season grasses in subsequent years. Since greater fuel moisture in live grass decreases burn intensity (Govender et al. 2006), we theorize that dry fuel resulting from herbicide application may have increased burn intensity, resulting in higher grass mortality and seed destruction. Burning alone (B1), without herbicide, ranked 6 at Hunewell and 9 at Muse for Texas wintergrass and 5 for brome at Hunewell. Ansley and Castellano (2007) and Whisenant et al. (1984) found that cool-season burning reduced biomass of Texas wintergrass after 1 yr, as opposed to warm-season burning; however, plant biomass levels returned to prefire levels within two growing seasons. Whisenant and Uresk (1990) found that spring burning reduced brome over several seasons. In our study, burning in the cool season constituted a cooler burn with higher leaf moisture of actively growing Texas wintergrass and brome, as observed with patchy burning and more smoke in the prescribed burn. For the longer term, repeated winter and early spring fires over several years shift community composition by reducing cool-season species and increasing warm-season species over time (Anderson et al. 1970; Howe 2000), which may not have been apparent in the duration of our study.

Timed cool-season, high-intensity, short-duration grazing was used as a treatment based on the hypothesis that it would suppress Texas wintergrass growth and seed production by lowering reserves with repeated grazing over two seasons. Hood (2019) found that grazing over two consecutive cool seasons increased bare ground and decreased Texas wintergrass cover and seed production as compared with control plots. We found that grazing alone (G2) ranked low at both Hunewell (9) and Muse (8) as a suppression treatment for Texas wintergrass. Timed high-intensity, short-duration grazing can stimulate growth in species adapted to grazing (Lemus 2011). For brome, it was considered moderately successful, with a ranking of 5. In combination with herbicide and burning, treatment H2B2G2 ranked 3 or higher across both sites at suppressing cool-season grasses. However, treatment H2B2 also ranked 3 or higher, making it difficult to distinguish if there was an added suppression benefit of grazing.

It is important to note that treatments were initiated directly following mesquite removal. Studies have shown an initial increase in Texas wintergrass for 2–3 yr following mesquite removal (Laxson et al. 1997; Ansley et al 2019), which may indicate that treatments applied in this study may have coincided with increased productivity, possibly affecting suppression efforts. We seeded directly following mesquite removal, since bare ground created with bulldozing was expected to be quickly colonized by ruderal species. We expect that if mesquite trees were treated with herbicide, without soil disturbance, it may be preferable to wait approximately 3 yr to begin seeding and suppression efforts.

Increase of Warm Season Grasses and Forbs

Treatments altered the growing environments for establishing seeded grasses and forbs. Herbicide as a single treatment created plant-attached litter (Fig. 3**A**). Litter can shade and ameliorate soil surface conditions in hot, dry environments, preventing desiccation, which may promote seeded species establishment at certain sites (Mollard et al. 2014). In our study, herbicide alone, ranked 2 (H2) and 3 (H1) for seeded grasses at Hunewell, while at Muse, H2 ranked 7 and H1 ranked 2. For seeded forbs at Hunewell, H2 ranked 3 while H1 ranked 10. Treatment H2 essentially resulted in two consecutive seasons of mulch. At Hunewell, H2 promoted seeded grasses and forbs over H1 and treatment combinations that remove litter with herbicide and burning. At Muse, the mulch effect may be less important since H2 ranked 7, behind all treatments that potentially removed attached litter.

Burning following herbicide, treatments H1B1 and H2B2, removed dead plant–attached litter (see Fig. 3B), exposing more soil surface. Early spring warming of bare soil can promote warm-season grass and forb establishment (Old 1969; Brockway et al. 2002). Treatment H2B2 essentially resulted in two consecutive seasons of bare soil. At Hunewell, H2B2 ranked 6 and H1B1 ranked 10 for increasing seeded grass cover, reinforcing evidence for a beneficial mulching effect at that site, since H1 and H2 ranked higher. Treatment H2B2 ranked 7 at Hunewell for forbs. At Muse, H2B2 ranked 5, failing to provide strong support for a benefit of bare soil; however, H2B2G2 ranked 1 at Muse. Burning as a single treatment (B1) ranked 9 at Hunewell and 8 at Muse for increasing seeded grasses, possibly related to a limited suppression effect on cool-season grasses. Although for forbs, treatment B1 ranked 2 at Hunewell.

Table 7
Overall rankings for treatments based on percent changes in cover of Texas wintergrass, brome, seeded grasses, and seeded forbs from pretreatment to one growing season post 2-yr treatments.

Hunewell	Decrease in Texas wintergrass				Decrease in brome				Increase in seeded grasses				Increase in seeded forbs					Per site Avg	Both sites Avg	Rank
Trt	Pre	2YP	% Chg	Rank	Pre	2YP	% Chg	Rank	Pre	2YP	% Chg	Rank	Pre	2YP	% Chg	Rank				
C	20.9	11.2	−46	5	22.4	26.4	18	9	2.2	25.7	1068	1	1.3	5.5	323	1	C	4	6.5	6
H2	20.4	6.6	−68	1	20.2	21.6	7	8	3.3	27	718	2	2	3.8	90	3	**H2**	3.5	4	**3**
H1	8.1	7.1	−12	8	28.6	39.6	38	10	5.7	29.7	421	3	1	0	−100	10	H1	7.8	5.6	4
B1	12.2	8.2	−33	6	32.2	25	−22	5	7.7	12.2	58	9	1	3.3	230	2	B1	5.5	6.5	6
H2B2	11.6	4.7	−59	3	24.6	8.5	−65	2	8.2	29.7	262	6	3.8	1.2	−68	7	**H2B2**	4.5	3.8	**2**
H1B1	15.8	6.5	−59	3	16	14.6	−9	7	11	16	45	10	4.7	5.7	21	5	H1B1	6.3	5.6	4
B1G2	10.3	22.2	116	10	24.8	13.5	−46	3	9.2	15	63	8	3.2	1	−69	8	B1G2	7.3	6.9	9
H2B2G2	12.2	4.4	−64	2	27.5	4.2	−85	1	5.2	23	342	4	3	5.7	90	3	**H2B2G2**	2.5	2.3	**1**
H1B1G2	15.5	12.8	−17	7	13	10.8	−17	6	5.3	22.8	330	5	3.3	1	−70	9	H1B1G2	6.8	6.9	9
G2	10.8	15	39	9	26.9	19.8	−26	4	5.5	12.2	122	7	2.3	2.4	4	6	G2	6.5	6.8	8
	Muse																			
Trt	Pre	2YP	% Chg	Rank					Pre	2YP	%Chg	Rank								
C	36.8	58.5	59	9					3.7	9.7	162	9					C	9		
H2	32.8	9.9	−70	2					4	18.2	355	7					H2	4.5		
H1	39.9	28.3	−29	5					1.2	12	900	2					H1	3.5		
B1	26.9	34.2	27	7					6.3	19	202	8					B1	7.5		
H2B2	35	7.6	−78	1					3.7	21.8	489	5					H2B2	3		
H1B1	36.3	32.1	−12	6					2.5	17.8	612	4					H1B1	5		
B1G2	27.9	46.4	66	10					2.8	20.8	643	3					B1G2	6.5		
H2B2G2	34.4	11.5	−67	3					1.3	14.8	1038	1					H2B2G2	2		
H1B1G2	39.4	24.9	−37	4					2.8	7	150	10					H1B1G2	7		
G2	27.4	37.9	38	8					2.3	11	378	6					G2	7		

C indicates control; H1, herbicide applied once; H2, herbicide applied twice; B1, burned once; G2, grazed twice.

Figure 3. **A,** Two wk post herbicide treatment; **B,** 2 wk post herbicide-burn treatment; **C,** 2 wk post herbicide-burn-graze treatment.

Grazing following herbicide and burning, treatments H1B1G2 and H2B2G2, essentially constituted trampling bare ground (see Fig. 3C). Treatment H2B2G2 ranked 4 at Hunewell and 1 at Muse, where grazing was deferred several years before the study, for increasing seeded grasses, and 3 at Hunewell for increasing forbs. Trampling associated with high-intensity short-duration grazing benefits C4 grass and forb establishment in spring and early summer (Fargione et al. 2003). Grazing alone (G2) ranked 7 at Hunewell and 6 at Muse for increasing seeded grasses. There appears to be a contribution of high-intensity, short-duration grazing and associated soil disturbance to the growing environment for seeded grasses and forbs beyond herbicide and burning alone. Relative to continuous grazing, rotational grazing has been found to increase soil carbon and decrease soil bulk density; however, effects are often only detectable in the long term (Byrnes et al. 2018). These benefits may be realized more rapidly with vegetation removed by herbicide and fire, freeing resources in the form of ash, which are then trampled into the soil.

Seeding

For conversion from cool-season to warm-season grasses, and to increase species diversity, seeding is often needed following removal of woody species (Monaco et al. 2005; Kyser et al. 2007; Sheley et al. 2007). The selection of seeded herbaceous species for the study area was based on NRCS ecological site historical reference communities (Soil Staff 2019). None of the seeded species were observed at either site before seeding or present in the nonseeded plots during the study. This indicates the lack of historical reference tall and midgrass species in the soil seed bank. In woody-encroached grasslands, the longer the time since encroachment, the lower the herbaceous species diversity (Ratajczak et al. 2012) and less likely that viable seeds of warm-season grasses and forbs exist in the soil seedbank (Rodriguez and Jacobo, 2013). We theorized that mesquite cover had been in place long enough, in combination with continuous grazing, at each site to allow the soil to be depleted of viable seeds of much of the historical reference community.

Overall Ranking

The end goal of this study was to promote native rangeland warm-season grasses and forbs over existing cool-season species. The effect of creating an improved growing environment for establishing seeded grasses and forbs may be difficult to separate from the effect of cool-season grass suppression, since competition from cool-season grasses was expected to limit establishment of seeded warm-season grasses. For that reason, we considered treatments or treatment combinations that ranked high across all categories as most successful. Across both sites, the three most successful treatments, in order, were H2B2G2, H2B2, and H2, respectively. The top treatment, H2B2G2, never ranked lower than 4 across all category rankings for each site based on decreasing Texas wintergrass, decreasing brome, increasing native seeded grasses, and increasing seeded native forbs. Also, H2B2G2 performed much better across all variables and sites than H1B1G2, which ranked overall 9. Treatment H1B1G12 was the only treatment with herbicide to rank low. Other low-ranking treatments included C, B1, G2, and B1G2. The unexplained increase in seeded grasses and forbs in the control at Hunewell kept the control from ranking lower in the overall rankings across both sites. This may have been driven by the microenvironments where mesquite that favored seedling establishment across all treatments had been removed. By contrast, at Muse, the control ranked last among treatments. Given the difference in ranking between H1B1G12 and H2B2G2, the possibility of a threshold exists. Treatment H1B1G2, ranked 9, essentially resulted in trampled bare ground in treatment Yr 1 followed by grazing cool-season regrowth in Yr 2. It behaved and ranked similar to the grazing alone (G2) treatment, possibly due to rapid regrowth of cool-season grasses. Treatment H2B2G2, ranked 1, resulted in 2 consecutive yr of trampled bare ground, freeing enough resources, long enough to better allow seeded species establishment.

Implications

Our goal was to develop best management practices to restore mesquite-Texas wintergrass areas back to diverse, native warm-season perennial grasslands to create better habitat for native grassland bird species. This 4-yr study used combinations of seeding, herbicide, fire, and high-intensity, short-duration grazing to determine the best restoration practices that can be conveyed to landowners. Findings indicate that treatments combining early-spring herbicide followed by burning and grazing over 2 consecutive yr most effectively reduced Texas wintergrass and brome percent cover and promoted native warm-season grass and forb establishment. Our findings indicate that herbicide is necessary to reduce Texas wintergrass and brome, which reduces competition with establishing seeded warm-season species. Burning following herbicide consistently further reduced brome beyond herbicide alone. However, establishment of seeded species was best promoted by the addition of high-intensity, short-duration grazing following herbicide and burning.

There are apparent benefits of a second consecutive yr of treatments that justify additional time, effort, and costs. Whether or not to burn following herbicide may be site dependent; warm-season seedling establishment may benefit from litter associated with herbicide without burning on harsher sites. The fact that timed grazing further promoted establishment of seeded grasses and forbs allows land managers the opportunity to continue grazing on an appropriately timed basis. Further long-term study on grazing is needed to assess the long-term impacts. Overall long-term monitoring of the research sites would provide information regarding long-term trends in conversion, with adaptive management expected.

Declaration of Competing Interest

None.

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