2019

Increasing Warm-Season Native Grass Biomass Using Fire, Herbicide, and Nitrogen Applications

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Abstract

The North American Great Plains tallgrass prairie was once a system of native cool and warm season grasses, which have been degraded by non-native invasive plants. Native grass restoration is highly desirable to improve ecosystem functions and productivity. In this two-year study, the impact of fire, herbicide, and nitrogen on productivity and the presence of invasive species [primarily the cool season grass, smooth brome (*Bromus inermis* Leyss.)] and native warm season native grass species [big bluestem (*Andropogon gerardii* Vitman), sideoats and blue grama (*Bouteloua curtipendula* (Michx.) Torr.), and *B. gracilis* (Willd. Ex Kunth) Lag. ex Griffiths] were investigated. Spring fire or a glyphosate application increased warm season grass biomass and decreased cool season grass biomass at peak warm season growth (August) during the treatment year. A second consecutive year of fire or herbicide further increased warm season grass biomass. If left untreated in the second year, cool season grasses tended to increase when sampled in August. Long-term management implementation is needed to suppress the tenacious cool season species and encourage the reestablishment of warm season grass populations.

Keywords: prairie restoration, glyphosate, *Bromus inermis* control, *Andropogon gerardii*

1. Introduction

The tallgrass prairie once covered 170 million acres in North America, but only about 4% remain [1–4]. The tall and mixed grass prairie systems have been in decline since European settlement, with human encroachment, population expansion, and overgrazing with insufficient recovery times contributing to the loss of native prairie acres [3–5]. In addition, the loss of natural disturbances, such as fire and grazing with bison, has decreased native plant presence and diversity in remnant prairie sites [3, 4, 6]. Other threats to this resource include fragmentation, as smaller parcels provide less continuity, and due to more isolated populations, an increase of deleterious genes in a community that reduce fitness [7]. The introduction of non-native species, either purposefully introduced or encroachment from neighboring areas, often dominate the ecosystem [8]. In South Dakota, non-native species are estimated to be present on 82% of its 9.7 million ha of rangeland, and account for at least 25% of the relative canopy cover on 22% of these areas.

Kentucky bluegrass (*Poa pratensis* L.) and smooth brome are typically cited as the most invasive cool season species in the Northern Great Plains, accounting for over 10% of all plant cover and 62% of exotic species cover [9, 10]. Infestations progress from scattered patches to over 90% of a pasture in 30 yrs. [11]. These C_3 species suppress native cool and warm season grass production and can create negative feedback cycles that increasingly perpetuate favorable microclimates for the invasive species, making restoration to natives increasingly difficult [12, 13]. Cool season grasses become dominant by breaking dormancy very early in the season and outcompeting later emerging plants for nutrients, water, and light [13, 14], and later, forming a thick thatch layer that does not readily decompose [12, 13, 15], which slows soil warming, shades the soil surface, and delays the growth of warm season plants [16, 17].

Management practices are needed that reduce invasive species competitiveness and enhance growth and productivity of native species [11, 18]. Spring burns remove thatch layers, allowing up to 40% more sunlight to reach the soil surface [17], which increases soil temperatures, provides more direct light to small plants that could be stunted by shading, and removes or sets back growth of cool-season species, thus reducing competition from larger more vigorous plants. Hulbert [19] reported that thatch removal and exposing the soil surface to light resulted in an increase of warm season species vegetative and reproductive productivity regardless of how the thatch was removed (e.g. clipped or burned). Native warm season grass biomass had greater response to burning (98% biomass increase) than to soil warming (8% biomass increase) [16]. Therefore, prescribed burns often are used to influence prairie species composition.

Timing of prescribed burns can be crucial in influencing species outcome. For example, long-term studies (>54 yrs) of annual Flint Hills (Kansas) burns report that late spring burns (May 1) increased later season biomass of warm-season grasses including big bluestem and Indiangrass (*Sorghastrum nutans* L. Nash), whereas sedges and perennial forb biomass decreased, as the burn time coincided with their emergence [20, 21]. However, early spring (March 20) and winter (December 1) burns favored annual and perennial forbs, and other grass species such as Scribner's panicum [*Dichanthelium oligosanthes* (J.A. Schulte) Gould var. *scribnerianum* (Nash) Gould], and little bluestem (*Schizachyrium scoparium* Michx.) [21]. In a Minnesota study, little bluestem did not change in biomass based on different fire frequency return times (1, 2, or 4 yr intervals) over 27 yr, although Kentucky bluegrass decreased with increasing fire frequency [22]. In South Dakota, Kentucky bluegrass biomass was reduced with either mid-May and mid-June burns, however, big bluestem biomass only increased after the early burn [23]. The dominant species of the starting community (e.g. smooth brome, Kentucky bluegrass, or warm-season grasses) also influences community composition response to different burn timings [24]. Results from these diverse studies indicate that individual plant and community responses to burn timing could assist or hamper land managers in their goal to manipulate species composition.

A second method of influencing grassland composition is adding or withholding nutrients, with or without prescribed burns [24–36]. Burning changes nutrient cycling [26, 27]. Supplemental N application rates and timings can influence species composition and forage production in range and pastures. For example, ammonium nitrate (NH_4NO_3) applied at 10 or 20 g/m^2 was used alone or combined with annual burns [28]. When fire was not used and N was added, forbs increased and exceeded grass production, but had little impact on total overall biomass. In treatments that were burned and received N, C_4 grasses dominated and total biomass increased by 68% [28]. However, the N rate needs to be closely monitored, as anthropogenic N deposition, principally through rainfall and attributed to industrialization, urbanization, and increased fertilizer use [29–31], has doubled the input of available N on the Earth's surface in the recent past [31]. Adding too much N, as little as 2.5 [30] to 10 [32] kg N ha^{-1} $yr.^{-1}$, can reduce native plant species numbers [32] especially those adapted to low soil N [33]. High soil N reservoirs present, especially early in the growing season, may lead to greater non-native plant invasion [34], as these plants tend to acquire and use N more efficiently, thus increasing their biomass and density [35] with a decline of native species growth. Once non-natives establish, a cascade of events may occur that render reversal to the original native community difficult, if not impossible. First, competition for water and other resources further reduces native species density, biomass, and species richness of a site [35]. This is followed by reduction in native species growth, which depletes the native seedbank and, finally, subtle changes of soil biological and chemical properties may occur that hinder repopulation by native plants [36].

Herbicides have also been used, alone and in combination with burns and N application, to control smooth brome and Kentucky bluegrass and manipulate native vegetation restoration [37–41]. Herbicide type, application timing, and rate have been examined in several studies. For example, Bahm et al. [38] used herbicides (imazapic, imazapyr, sulfosulfuron) alone or in combination with spring and fall applications to target smooth brome and Kentucky bluegrass. Herbicide treatments were compared to a fall burn or non-treated control. They reported that burn alone did not reduce either grass species, but spring or fall applications of most herbicides reduced smooth brome from 64% cover to 10% cover after 3 years of treatment. Although Kentucky bluegrass was more recalcitrant than smooth brome in several studies [38, 39], native grass cover or species richness increased in treatments. Others have reported greater control of smooth brome with atrazine applied in spring [40] although native grasses were less injured with a fall application of glyphosate [41].

Prescribed burns with modest applications of fertilizer have been shown to sustain and increase native grass species biomass and forage production, improve wildlife habitat, and decrease the need for weed management in more southern, western, and northern U.S. regions [8, 20–34, 40–41]. However, fewer studies have been performed in the Northern Great Plains [38, 39] where soils, plant composition, rainfall, and temperatures widely differ. The objective of this study was to examine the influence of combinations of burn, herbicide application (fall or spring), and N application (spring, summer, or fall) on non-native cool season grass competition and biomass, and native warm season grass biomass.

2. Using fire, herbicide, and nitrogen to manipulate cool and warm season grasses

2.1 Methods and materials

2.1.1 Site description

Two sites were used in this experiment, one in far-eastern South Dakota at Volga (N 44°23′1.53“, W 96°57’29.39”) and a more western site (100 km west and 50 km south of Volga) at Artesian (N 44°5.80′, W 97°54.56′). Both sites have hot summers with temperatures exceeding 32°C, periodic summer droughts, and cold (air temperatures as low as −40°C) snowy winters.

The Artesian site, located in Sanborn County was used for cut hay and pasture. The soil type was predominantly Houdek-Dudley complex (fine-loamy, mixed Typic Argiustolls and fine, mixed Typic Natrustolls) with a 0–9 percent slope [42] and is glacial till loamy claypan with thin uplands and wet meadows. The plots were in upland positions. The dominant species were Kentucky bluegrass and smooth brome, with big bluestem, sideoats grama, and little bluestem present in plot area.

The Volga site, in Brookings County, was located on a heavily cool-season grass infested remnant prairie surrounded by pasturelands and was rotationally grazed. The soil mapping unit was a Buse-Poinsett complex (fine-loamy, mixed Typic Calciudolls and fine-silty, Calcic Hapludolls) [42] that has an ecological description as a thin loamy soil. Plots were located at the summit and shoulder-slope positions in an area with a 2–10 percent slope, although shallow marshes and wet meadows were also present at the site. Dominant grass species prior to treatment included smooth brome and Kentucky bluegrass. Big bluestem and sideoats grama were present, but not abundant, in the pretreatment survey of vegetative composition.

2.1.2 Experimental design and treatments

The experimental design was a randomized split-block (12 by 6 m) split-plot with four replications. The main effect treatments were fire, N, and herbicide application with each main plot split into four subplots (6 by 3 m). Plot areas were selected and established in fall 2009 (Location 1) and fall 2010 (Location 2). Location 1 plots were treated in the fall of 2009 with herbicide or N in the appropriate plots, and then in spring 2010 with the remaining treatments (designated as YR1). Location 1 plots at the Artesian site were subdivided in fall 2010 with half the plot 'recovering' (RECOVERY) from the 2010 treatment (i.e. no further treatment), and the other half treated (in fall 2010, when appropriate, and spring 2011) for a second year with the same treatment (YR2). Location 2 plots were a repeat in time of the YR1 treatments (Volga and Artesian).

2.1.3 Fire treatments

The two main fire treatments were 1) not burned or 2) burn in the spring. The fire main plots were then divided into four subplots with treatments of N: (1) no N applied; or N applied at 25 kg N ha^{-1} as NH_4NO_3 (2) in October prior to burn; (3) in April prior to burn, to stimulate cool season grass growth to maximize injury, or (4) in June after the burn to stimulate warm season species growth.

The spring burn was conducted between April 21 to May 9 (2010 and 2011) and depended on vegetative development, dryness, and wind speed for safety. The fires were started with a drip-torch and back burned or using a weed burner. Water was applied around the plot edges, and a fire crew was present on plot perimeters with spray equipment to contain the fire within a plot area. Thatch depths at Volga averaged 22 cm (±6), and 15 cm (± 1) in 2010 and 2011, respectively, just prior to the burn. At Artesian, thatch depths were 4 cm (±2) (2010 YR1), 13 cm (±3) (2011 YR2), and 15 cm (±3) (2011 YR1). Fire temperatures [monitored by placing four slides painted with Tempilaq thermopaints (LA-CO Industries, Elk Grove, IL, USA) at the soil surface per plot] ranged from 79 to 343°C (average = 219°C) at Volga and from 79 to 325°C (average = 198°C) at Artesian.

2.1.4 Nitrogen treatments (no fire/no herbicide)

The nitrogen block was split into four treatments. The treatments were no N, 25 kg N ha^{-1} as NH_4NO_3 applied in April or June, and a double treatment, 25 kg N ha^{-1} applied first in October and then the following April.

2.1.5 Herbicide treatments

The herbicide treatment was glyphosate (applied with ammonium sulfate and nonionic surfactant). The main herbicide treatment plot was divided into subplots based on times of herbicide and N application (base rate of 25 kg N ha^{-1}). The treatments were herbicide October/no N; herbicide May/no N; April N followed by (F/B) herbicide May; herbicide May F/B June N. The October glyphosate rate was 1.5 kg ai ha^{-1} applied after warm season grass senescence but prior to killing frost. The April/May rate was 0.38 kg ai ha^{-1} applied after cool season grass emergence, but prior to emergence of warm season grasses.

2.1.6 Data collection

At both sites, baseline vegetative biomass was collected during the peak of warm-season growth (late August/early September) in 2009 prior to treatment application. Vegetation samples were cut at soil surface in three 0.25 m^2 quadrats per main plot. Samples were dried at 32°C until constant weight and separated into functional groups of native grasses, non-native species (mostly grasses), and forbs, and weighed.

After spring treatments, visual cover assessments of warm season grass, cool season grass, and forb were evaluated twice during 2010 and 2011: at the peak of cool season grass growth (mid/late June) and at the peak of warm season grass growth (late August/early September). The percentages of bare-ground and litter were estimated. At the Artesian site, all plots [YR1, Location 1 and 2; YR2 and Recovery (Location 1)] were sampled with vegetation cut from a 0.25 m^2 quadrat after both cool and warm season grass peak growth assessments. At the Volga site, species cover at peak cool season grass development was visually assessed. Vegetative sampling occurred in the YR1 Location 1 and 2 plots at peak warm season growth in August of each year. These vegetation samples were dried, separated into functional groups as described above, and weighed.

2.1.7 Statistical analysis

PROC MIXED and PROC GLM [43] were used to analyze the data by site, location, and sampling date to calculate the difference of least mean square and determine differences among treatments. To determine if treatments over time accelerated warm season grass growth and decreased cool season non-native grass growth, repeated measure ANOVA was used in SAS with a PROC MIXED statement. This analysis helped determine variation among samples, variation among sample timing, and residual variation [44]. The repeated measures design uses the control from each sampled subject and has been called within-subjects ANOVA or randomized-blocks ANOVA [45]. The null hypothesis for this study was H_0: $\mu_1 = \mu_2 = \ldots = \mu_i$, i.e. treatments would not influence estimated cover or vegetative biomass compared with the untreated control.

2.2 Results

2.2.1 Climate

2.2.1.1 Artesian

In 2009, prior to the October N treatment, the average temperatures for the growing season were about 2°C below the 30 yr (1971–2001) average, whereas precipitation ranged from 4 to 8 mm above the 30 yr average for June, July, and August [46]. Growing degree days (base 10°C) from 15 April to 15 September were 5% above the 30 yr normal of 1240 GDD in 2010 and 5% below normal for 2011. Precipitation from January through August totaled 483, 940, and 454 mm for 2009, 2010, and 2011, respectively, compared with the 30 yr average of 428 mm.

2.2.1.2 Volga

Temperatures and rainfall for 2009 were near the 30 yr average of 1154 GDD and 439 mm, respectively [46]. The 2010 and 2011 seasons were warmer and wetter than the 30 yr average. GDD for 15 April to 15 September for 2010 and 2011 were about 10% above the 30 yr average each year. January through August precipitation for 2010 and 2011 was much greater than the 30 yr average and totaled 720 (+64%) and 568 (+30%) mm, respectively.

2.2.2 Treatment response - artesian

2.2.2.1 Baseline sampling

In August 2009 during visual assessment at warm season peak growth, warm and cool season grass canopy covers were similar, each occupying about 50% of the canopy. Biomasses of these functional groups were similar and averaged 145 g m^{-2} (± 82) for warm season grasses and 179 g m^{-2} (± 88) for cool season grasses. In April 2010 before spring treatments, baseline visual cover assessments were similar among blocks, with warm season and cool season grass covers estimated at 30 and 65%, respectively. However, warm and cool season grass biomasses were similar and averaged 123 (± 73) and 96 g m^{-2} (± 62), respectively.

2.2.2.2 One year of treatment

Due to differences in precipitation between 2010 and 2011 (i.e. 2010 had 150% more rainfall than 2011), Location 1 and 2 data were analyzed by year. The cool and warm season grass biomass in late June 2010 (peak cool season biomass) averaged 181 (± 74) and 41 (± 9) g m^{-2} in control plots (**Figure 1A**). Fire alone and April N FB fire reduced cool season biomass to about 30 (±6) g m^{-2}, whereas cool season biomass averaged 107 (±12) g m^{-2} in the October N FB fire and fire FB mid-June N treatments (**Figure 1A**). A visual example of the plots pre- and post-fire is provided in **Figure 2**. Glyphosate applied in May alone or FB June N reduced cool season biomass. Warm season biomass was greater than the control in all glyphosate treatments, expect when FB June N application. Nitrogen treatments applied in April or June N averaged 388 (±25) g m^{-2} of cool season grass biomass, twice as much compared with control plots.

At the peak of warm season grass (August 2010) (**Figure 1B**), warm season and cool season grass biomass in control plots averaged 173 and 149 g m^{-2}, respectively. Fire alone or in combination with any N treatment increased warm season grass biomass by at least 120% and decreased cool season biomass by about 50%. The April N FB glyphosate had the greatest warm season biomass of any treatment and averaged over 450 g m^{-2}. Other herbicide treatments had warm and cool season grass biomass that was similar to the control. The June N treatment increased both warm and cool season biomass and April N had similar warm season biomass to the control but also increased cool season grass biomass.

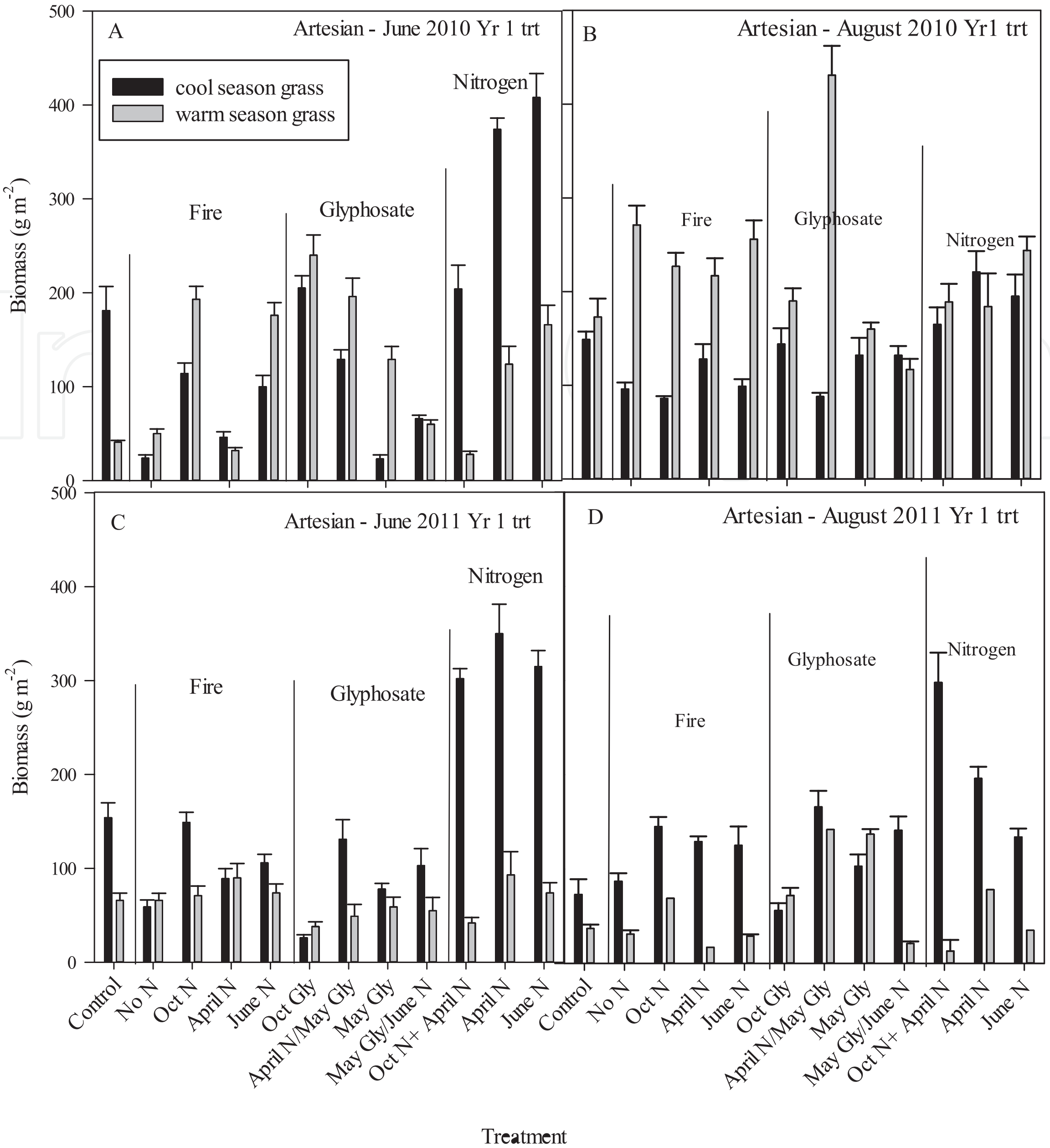

Figure 1.
Cool and warm season grass biomass by treatment and year in June [(A) 2010; (C) 2011] and August [(B) 2010; (D) 2011] samplings after a single year of treatment at Artesian, SD.

In June 2011, the fire treatments reduced cool season grass biomass, except when N was applied the previous October (**Figure 1C**). Glyphosate treatments, except for April N FB glyphosate, also had a cool season biomass reduction. The N treatments alone, however, stimulated cool season grass growth and did not stimulate growth of warm season species. Unlike 2010 when warm season growth showed an increase at the August sampling with many treatments, most treatments had greater cool season biomass with all N treatments having the greatest amounts (**Figure 1D**). The yearly differences between the treatments were partly due to the lower rainfall in 2011 and a heavy infestation of the biennial, sweet clover [*Melilotus officinalis* (L.) Lam.], which bolted and shaded out both native and non-native grasses throughout the entire location.

2.2.2.3 Two years of treatment

After two consecutive years of fire treatment at location 1, when sampled in August (peak of warm season species growth) (**Figure 3A**), October N F/B spring

Figure 2.
Example of a fire plot at Artesian, SD, (A) Prefire in April, with cool season invasive grasses present (B) during fire treatment, (C) about two weeks post-fire, (D) native warm season grass growth, August sampling, 2010.

fire had the least cool season grass biomass, (reduced by 37%) and the greatest warm season biomass. Glyphosate applied in May had the greatest warm season grass biomass of all the treatments. Applying N in April FB May glyphosate resulted in less warm season grass biomass. When N followed glyphosate application, cool season grasses, rather than warm season, appeared to be stimulated. Nitrogen alone resulted in greater cool season grass biomass even in August.

2.2.2.4 Recovery after one year of treatment

In the June sampling, most plots had high amounts of cool season grass and low warm season grass presence (**Figure 3B**). In the August sampling, warm season grasses in all fire plots, except fire FB June N, had greater warm season and less cool season grasses (**Figure 3C**). The glyphosate and nitrogen treatments had

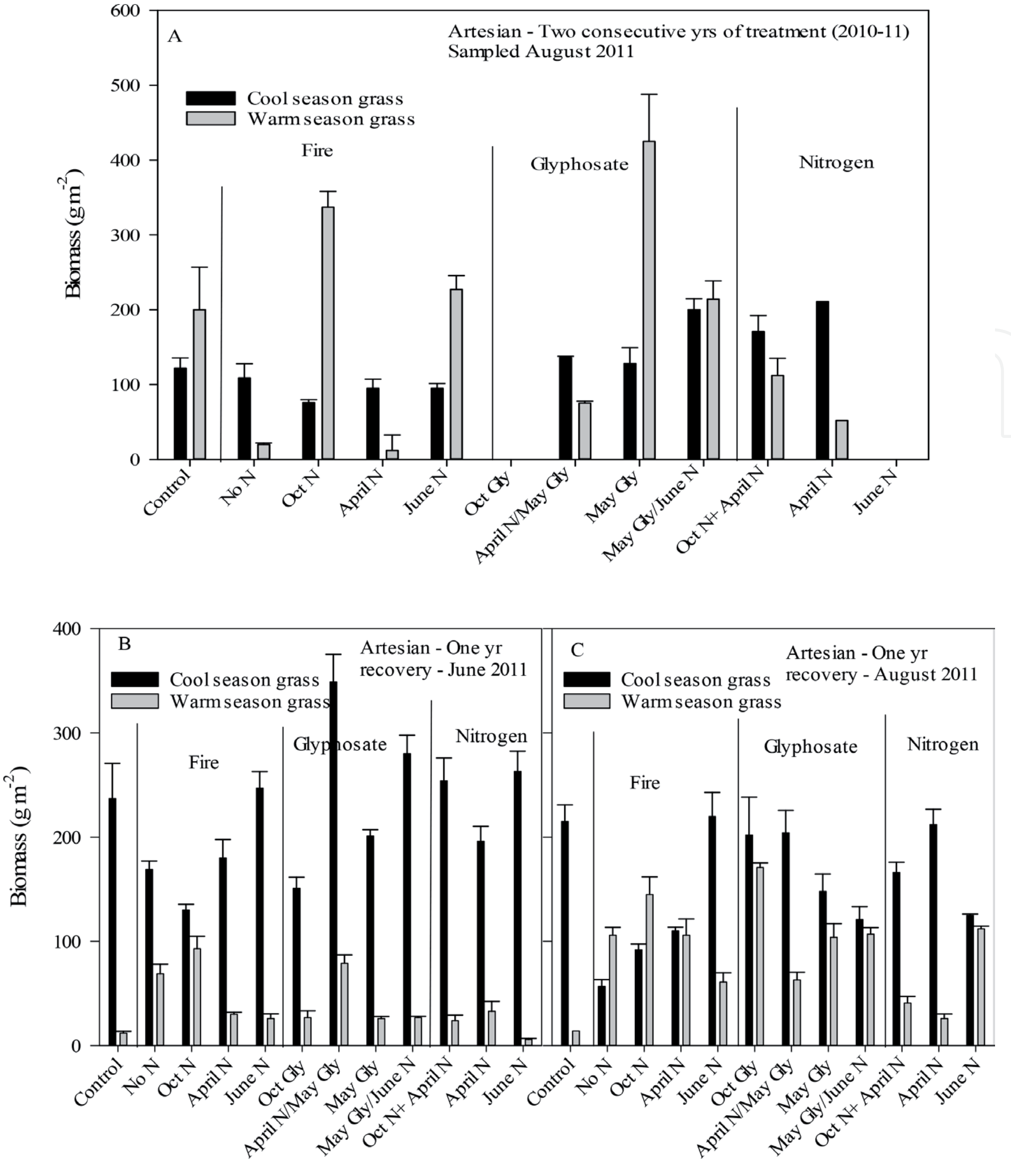

Figure 3.
Cool and warm season grass biomass in August sampling after two consecutive years of treatment (A), and in recovery plots (treated in 2010) for June (B) and August (C) of 2011.

greater warm season grass biomass than the control, but little reduction in cool season grass biomass.

2.2.3 Treatment response - Volga

2.2.3.1 Baseline data

Baseline data collected in the fall of 2009 (for Location 1 plots) and 2010 (for Location 2 plots) had visual cover estimations for warm season grass species at 35%, cool season grass species 65%, and 5% forbs.

2.2.3.2 One year of treatment

At location 1 (2010 treatments), visual assessments of canopy cover were similar among the control and all treatments at the June sampling date (data not shown).

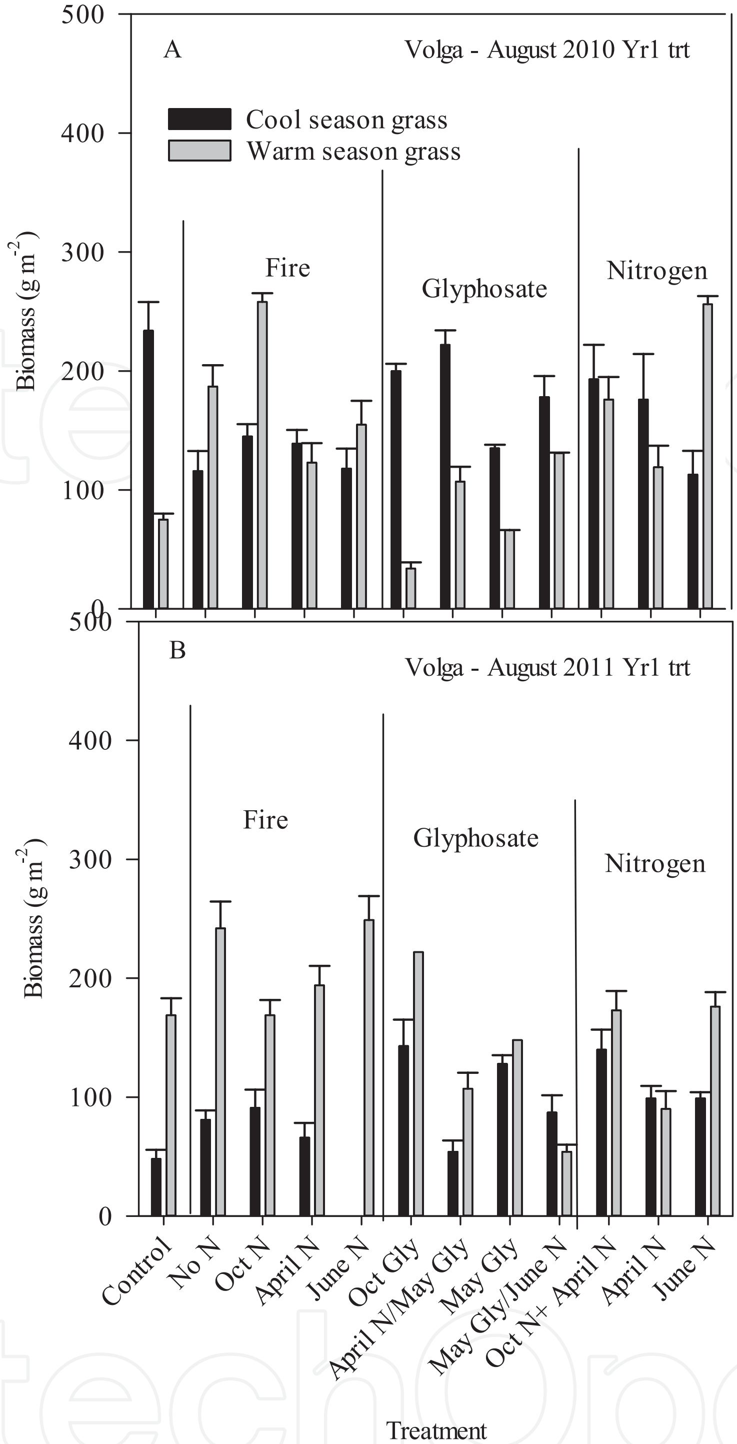

Figure 4.
Cool and warm season grass biomass by treatment sampled in August of 2010 and 2011 after the first year treatment at Volga, SD site.

Warm season grass biomass was 50 to 150% greater in fire treatments and had better cool season grass control in 2011 than 2010 (**Figure 4A** and **B**). Warm season grass biomass in the glyphosate and N treatments were similar to the control. Cool season grass biomass at the August 2010 sampling was reduced by all fire treatments, but all other treatments in 2010 and all treatments in 2011 had cool season grass biomass that was almost equal to the control.

2.2.3.3 Two years of treatment and recovery

After two years of treatment, visual cover assessments in all treatments were similar to the control. Biomass differences from the control were seen as an increase in warm-season grass species when October N was followed by the spring fire treatment (+1613%, $P < 0.05$), although cool season grass biomass did not differ from the control. Recovery plots at Volga did not show any differences from the control for either estimated cover or biomass.

3. Discussion

The introduction of cool season non-native aggressive grasses to the Northern Great Plains has reduced the warm season native grass component of the tallgrass prairie. In this study, fire, herbicide, and nitrogen treatments, alone and in combination with different application timings were used to examine the response of both the cool season invasive species and the warm season desired species with one year of treatment, two consecutive years of treatment, and the recovery response of the grasses if only treated one year. At both Artesian and Volga, the dominant native species was big bluestem, with lesser amounts of sideoats grama, and blue grama. These species have been reported to benefit from late spring burns [21] and our study agrees with those findings.

Prescribed burns removed the litter layer, allowed soil warming, and increased light reaching the soil surface, with concomitant increases in plant growth, all reported to increase warm season species growth [16]. In three out of the four first year plots, spring burns with or without N increased warm season species biomass as observed in August of the treatment year. The exception was Artesian 2011 first year plots, when sweet clover dominated all plots at both the June and August samplings. April N FB glyphosate increased warm season grass biomass in August 2010 but this response was not as pronounced in 2011. Warm season grasses at the both sites benefited from the two consecutive years of fire, but in Artesian, October N FB fire or fire FB June N was best, whereas at Volga, fire with no N was the best treatment. However, because litter depth is typically less after the first year of fire, lethal heat (>60°C) [47] at the soil surface tends to be longer if fire return times are biennial rather than annual [48]. Glyphosate applied for two consecutive years also aided in warm season grass growth. However, N alone would not be recommended, as cool season grasses dominated in all these plot areas. Recovery plots treated only with fire had increased warm season species biomass compared with control areas at both sites. Nitrogen application either before or after the fire treatment did not benefit warm season grass growth.

Vinton and Goergen [49] reported that smooth brome has a competitive advantage over native tallgrass species due to increased efficiency to cycle N. This characteristic may increase the persistence of smooth brome due to N deposition due to anthropogenic factors. Throughout this experiment, the application of N alone at any timing increased cool season grass biomass.

We were hopeful that cool season species would be more prone to fire or herbicide injury following either October or April N application. Increased injury to the cool season species (as observed by decreases in cool season biomass) only was observed in a few select treatments. In addition, the N added after fire or herbicide was, in theory, supposed to invigorate the warm season grass growth, as cool season grass growth should have been slowed, leaving the N for the late emerging species. However, adding N in June had limited success in increasing warm season grass growth, as observed at the Volga site in both years.

4. Implications and conclusions

Warm season grass growth had the most consistent positive response to fire, which also helped reduce the cool season non-native grass species. The application of fire, however, is not without risk, needs to be carefully utilized, and only applied when weather conditions are optimal and with trained personnel. There may be other considerations when using prescribed burns [50] and local fire officials, neighbors, and state agencies may need to be consulted and notified the day of the burn [51]. Nevertheless, prescribed burns may provide land managers and producers a simple and inexpensive way to reinvigorate the tallgrass prairie in eastern South Dakota. Location, soil type, species present, land use history, timing, temperature, and duration of fire [21–23, 48, 52], and the presence and number of active buds on the perennial grass tillers [24, 53, 54] are components that influence the restoration of areas to warm season native grasses, or maintain the continued presence of the cool season invasive species. Two years of consecutive treatment was more effective for warm season grass restoration than a single year, as seen by the rapid return of cool season grasses in the recovery plots. In addition, at times, a setup fall treatment of nitrogen or non-selective herbicide applied prior to the spring treatment may benefit warm season grass response, although these management options need further study.

Acknowledgements

Partial funding provided by SDSU Ag Experiment Station, NCR-SARE – 2010 Graduate Student Award, and USDA/CSREES Grassland grant #2008-38415-19596. Project field work was conducted by former master degree graduate student Ms. Shauna Waughtel-Johnson. Thanks to Dr. Michelle Ohrtman for help with data analysis.

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References

[1] US Park Service [Internet]. 2019. Available from: https://www.nps.gov/tapr/index.htm [Accessed: 01 March 2019]

[2] Blankenship B, Bradshaw M, Hinkle M, Schaub R [Internet]. 2019. What Are Some of the Thinkgs That Threaten Prairies and Contribute to Their Loss or Destruction? Available from: https://www.asc.ohio-state.edu/accad/womenandtech/2004/research%20pages/Loss/loss.html [Accessed: 15 February 2019]

[3] Robertson KR, Anderson RC, Schwartz MW. The tallgrass prairie mosaic. In: Schwartz MW, editor. Conservation in Highly Fragmented Landscapes. Boston, MA: Springer; 1997

[4] Risser PG, Bimey EC, Blocker HD, May SW, Parton WJ, Wiens JA. The True Prairie Ecosystem. Stroudsburg, Pennsylvania: Hutchinson Ross; 1981

[5] Albertson FW. Man's disorder of nature's design in the great plains. Transactions of the Kansas Academy of Science. 1949;**52**:117-131

[6] Howe HF. Managing species-diversity in tallgrass prairie-assumptions and implications. Conservation Biology. 1994;**8**:691-704

[7] Mannouris C, Byers DL. The impact of habitat fragmentation on fitness-related traits in a native prairie plant, *Chamaecrista fasciculata* (Fabaceae). Biological Journal of the Linnean Society. 2013;**108**:55-67

[8] Bock JH, Bock CE. Tallgrass prairie: Remnants and relicts. Great Plains Research. 1998;**8**:213-230

[9] [USDA] U.S. Department of Agriculture 2018 National Resources Inventory Rangeland Resource Assessment. Natural Resources Conservation Service. Washington, DC. Available from: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/nra/nri/results/?cid=nrcseprd1343028 [Accessed: 15 March 2019]

[10] Cully AC, Cully JF Jr, Hiebert RD. Invasion of exotic plant species in tallgrass prairie fragments. Conservation Biology. 2003;**17**:990-998

[11] Grant TA, Flanders-Wanner B, Shaffer TL, Murphy RK, Knutsen GA. An emerging crisis across northern prairie refuges: Prevalence of invasive plants and a plan for adaptive management. Ecological Restoration. 2009;**27**:58-65

[12] Sather N. Element Stewardship Abstract for *Bromus inermis*. Arlington, VA: The Nature Conservancy; 1987. Available from: http://www.invasive.org/weedcd/pdfs/tncweeds/bromine.pdf [Accessed: 05 March 2019]

[13] Toledo D, Sanderson M, Spaeth K, Herndrickson J, Printz J. Extent of Kentucky bluegrass and its effect on native plant species diversity and ecosystem services in the northern great plains of the United States. Invasive Plant Science and Management. 2014;**7**:543-552

[14] Benson EJ, Hartnett DC. The role of seed and vegetative reproduction in plant recruitment and demography in tallgrass prairie. Plant Ecology. 2006;**187**:163-177

[15] Hendrickson JR, Lund C. Plant community and target species affect responses to restoration strategies. Rangeland Ecology & Management. 2010;**63**:435-442

[16] Hulbert LC. Causes of fire effect in tallgrass prairie. Ecology. 1988;**69**:46-58

[17] Knapp AK. Post-burn differences in solar radiation, leaf temperature and water stress influencing production in a lowland tallgrass prairie. American Journal of Botany. 1984;**71**:220-227

[18] Taylor RV, Pokorny ML, Mangold J, Rudd N. Can a combination of grazing, herbicides, and seeding facilitate succession in old fields? Ecological Restoration. 2013;**31**:141-143

[19] Hulbert LC. Fire and litter effects in undisturbed bluestem prairie in Kansas. Ecology. 1969;**50**:874-877

[20] McMurphy WE, Anderson KL. Burning Flint Hills Range. Journal of Range Management. 1965;**18**:265-269

[21] Towne G, Owensby C. Long-term effects of annual burning at different dates in ungrazed Kansas tallgrass prairie. Journal of Range Management. 1984;**37**:392-397

[22] Li W, Zuo X, Knops JMH. Different fire frequency impacts over 27 years on vegetation succession in an infertile old-field grassland. Rangeland Ecology & Management. 2013;**66**:267-273

[23] Engle DM, Bultsma PM. Burning of northern mixed prairie during drought. Journal of Range Management. 1984;**34**:398-401

[24] Hendrickson JR, Lund C. Plant communities and target species affect responses to restoration strategies. Rangeland Ecology & Management. 2010;**63**:435-442

[25] Boughton EG, Bohlen PJ, Maki JH. Effects of experimental season of prescribed fire and nutrient addition on structure and function of previously grazed grassland. Journal of Plant Ecology. 2017;**11**:576-584

[26] Turner CL, Blair JM, Schartz RJ, Neel JC. Soil N and plant response to fire, topography, and supplemental N in tallgrass prairie. Ecology. 1997;**78**:1832-1843

[27] Risser PG, Parton WJ. Ecosystems of the tallgrass prairie: Nitrogen cycle. Ecology. 1982;**65**:1342-1351

[28] Seastedt TR, Briggs JM, Gibson DJ. Controls of nitrogen limitation in tallgrass prairie. Oecologia. 1991;**87**:72-79

[29] Wedin D, Tilman D. Competition among grasses along a nitrogen gradient: Initial conditions and mechanism of competition. Ecological Monographs. 1993;**63**:199-229

[30] Stevens CJ, Dise NB, Mountford JO, Gowing DJ. Impact of nitrogen deposition on the species richness of grasslands. Science. 2004;**303**:1876-1879

[31] Vitousek PM, Aber JD, Howarth RW, Likens GE, Matson PA, Schindler DW, et al. Human alteration of the global nitrogen cycle: Sources and consequences. Ecological Applications. 1997;**7**:737-750

[32] Clark CM, Tilman D. Loss of plant species after chronic low-level nitrogen deposition to prairie grasslands. Nature. 2008;**451**:712-715

[33] Gotelli NJ, Ellison AM. Nitrogen deposition and extinction risk in the northern pitch plant, *Sarracenia purpurea*. Ecology. 2002;**83**:2758-2765

[34] Vasquez E, Sheley R, Svejcar T. Creating invasion resistant soils via nitrogen management. Invasive Plant Science and Management. 2008;**1**:304-314

[35] Brooks ML. Effects of increased soil nitrogen on the dominance of alien annual plants in the Mojave desert. Journal of Applied Ecology. 2003;**40**:344-353

[36] Estrella S, Kneitel JM. Invasion age and invader removal alter species cover and composition at the Suisun tidal marsh, California, USA. Diversity. 2011;**3**:235-251

[37] Gillen RL, Rollins D, Stritzke JF. Atrazine, spring burning, and nitrogen for improvement of tallgrass prairie. Journal of Range Management. 1987;**40**:444-447

[38] Bahm MA, Barnes TG, Jensen KC. Herbicide and fire effects on smooth brome (*Bromus inermis*) and Kentucky bluegrass (*Poa pratensis*) in invaded prairie remnants. Invasive Plant Science and Management. 2011;**4**:189-197

[39] Link A, Kobiela B, DeKeyser S, Huffington M. Effectiveness of burning herbicide, and seeding toward restoring rangelands in southeastern North Dakota. Rangeland Ecology & Management. 2017;**70**:599-603. DOI: 10.1016/j.rama.2017.03.001

[40] Willson GD, Stubbendieck J. Suppression of smooth brome by atrazine, mowing, and fire. The Prairie Naturalist. 1996;**28**:13-20

[41] Anderson B. Converting smooth brome pasture to warm-season grasses. In: Proceedings of the Thirteenth North American Prairie Conference, Windsor, Ontario. 1994. pp. 157-160

[42] NRCS, USDA. 2019. Web Soil Survey. Soil Series Classification: View by Name. Available from: http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx [Accessed: 25 January 2019]

[43] SAS Institute Inc. SAS Software for Windows, v. 9.2. Cary, NC: SAS Institute, Inc.; 2008

[44] Hinkle DE, Wiersma W, Jurs SG. Applied Statistics for the Behavioral Sciences. 5th ed. Boston, MA: Houghton Mifflin Company; 2003

[45] Vogt WP. Dictionary of Statistics and Methodology: A Non-Technical Guide for the Social Sciences. 3rd ed. Thousand Oaks, CA: Sage Publications. 2005. pp. 259-268

[46] High Plains Regional Climate Center [Internet] Brookings (2NE, ID 391076) and Forestburg (3NE ID 393029), South Dakota Climate Summary 2011. Available from: https://hprcc.unl.edu/ [Accessed: 16 September 2012]

[47] Vermeire LT, Rinella MJ. Fire alters emergence of invasive plant species from soil surface deposited seeds. Weed Science. 2009;**57**:304-310

[48] Ohrtman MK, Clay SA, Smart AJ. Surface termperatures and durations associated with spring prescribed fires in eastern South Dakota tallgrass prairies. American Midland Naturalist. 2015;**173**:88-98

[49] Vinton MA, Goergen EM. Plant-soil feedbacks contribute to the persistence of *Bromus inermis* in tallgrass prairie. Ecosystems. 2006;**9**:967-976

[50] Randall J, Harr R. Considerations for Prescribed Burning: Ignition Techniques. Iowa State University Extension. 2012. PMR2088E. Available from: https://www.extension.iastate.edu/forestry/publications/pdf_files/pm2088e.pdf [Accessed: 20 March 2019]

[51] Porter M. How to Conduct a Prescribed Burn. 2000. Available from: https://www.noble.org/news/publications/ag-news-and-views/2000/february/how-to-conduct-a-prescribed-burn/ [Accessed: 15 March 2019]

[52] Vermeire LT, Russell ML. Seasonal timing of fire alters biomass and species composition of northern mixed prairie. Rangeland Ecology & Management. 2018;**71**:714-720

[53] Russell ML, Vermeire LT, Ganguli AC, Hendrickson JR. Fire return interval and season of fire alter bud banks. Rangeland Ecology & Management. 2019;**72**:542-550

[54] Ott JP, Butler JL, Rong Y, Xu L. Greater bud outgrowth of *Bromus inermis* than *Pascopyrum smithii* under multiple environmental conditions. Journal of Plant Ecology. 2017;**10**:518-527