NOVEL ECOSYSTEM MANAGEMENT: EVIDENCE FOR ALTERNATIVE STRATEGIES IN THE NORTHERN GREAT PLAINS

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MASTER OF SCIENCE

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ABSTRACT

Kentucky bluegrass (*Poa pratensis*, hereafter bluegrass) invasion in the northern Great Plains is reducing biodiversity and altering ecosystem properties. We cannot remove bluegrass from this system due to the extent of its invasion, so managers must control bluegrass invasion locally. However, effective management of bluegrass-invaded systems is unclear as they are novel ecosystems with no historic reference to guide current practices. First, we compared the influence of traditional and alternative grazing management strategies on invaded plant communities. Second, we quantified bluegrass fuel bed characteristics to inform prescribed fire management. Our findings indicate that alternative grazing management may be necessary to control bluegrass invasion and that restoring the fire and grazing interaction is a viable option. However, bluegrass fuel characteristics may challenge the implementation and success of prescribed fire management. As a whole, our findings reinforce the need for research on alternative management strategies for the conservation of imperiled ecosystems.

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DEDICATION

I dedicate this work to the glory of God and to the memory of my mother, Paula Lee (Hutchison) Endreson-Salter, for inspiring me to persevere against the odds.

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GENERAL INTRODUCTION: RESTORING HISTORIC DISTURBANCES TO MANAGE A NOVEL ECOSYSTEM

Over the past thirty years, Kentucky bluegrass (*Poa pratensis*; hereafter bluegrass) has inconspicuously invaded northern Great Plains rangelands. This exotic, perennial, cool-season grass is not only homogenizing rangeland vegetation by displacing native species but is also developing novel ecosystems with species assemblages and ecosystem properties that differ from historic conditions (Toledo et al. 2014). Specifically, bluegrass invasion develops a thickened thatch layer between the soil surface and plant canopy due to an imbalance between production and decomposition of bluegrass litter (Murray and Juska 1977; Toledo et al. 2014). Thatch acts as a positive feedback for bluegrass invasion as it buffers environmental conditions experienced at the soil surface and inhibits the germination of other plant species by altering various ecosystem properties (Toledo et al. 2014). The consequences of bluegrass invasion for ecosystem services are largely unknown and speculative. However, climate change is projected to increase the length of dry periods (Alexander et al. 2006; Deguines et al. 2017) and there is evidence to suggest that bluegrass dominance will increase the susceptibility of forage production to drought (Hockensmith et al. 1997). Bluegrass invasion has surpassed the possibility of eradication, so management should instead focus on promoting native biodiversity and maintaining ecosystem services (Toledo et al. 2014). Active management with fire and grazing has the potential to control Kentucky bluegrass while also promoting native plants and maintaining livestock production.

Without active management, Kentucky bluegrass invasion will result in the simplification of northern Great Plains plant communities (Toledo et al. 2014). Traditional-grazing systems (e.g. season-long grazing) promote uniform forage utilization and evidence reveals that they also promote bluegrass invasion (Smith and Owensby 1978). Early-intensive grazing has the potential to control bluegrass (Smith and Owensby 1978), but may not support adequate livestock production in the northern Great Plains (Grings et al. 2002). Research indicates that a single application of prescribed fire reduces bluegrass, but only for the first year after fire (Abrams 1988; Kral et al. 2018). Thus, additional disturbance (e.g. grazing) may be necessary to maintain the benefits of burning beyond two years (Bahm et al. 2011). Therefore, management involving the interaction of fire and grazing may be necessary, as neither fire nor grazing alone are enough to control bluegrass long-term.

Historically, fire and grazing shaped and maintained Great Plains rangelands (Samson et al. 2004). Their complex interaction developed a natural mosaic of areas in different stages of regrowth across the landscape. Wild grazing animals selected recently burned areas, while fire probability increased where litter accumulated (Fuhlendorf and Engle 2004). Consequently, most native grassland species are fire tolerant and able to withstand grazing after burning without needing rest (Limb et al. 2011a). Patch-burn grazing in today's fenced rangelands mimics this natural pattern by applying fire to a different portion of a pasture each year (Fuhlendorf and Engle 2004). Grazing is then concentrated on a small area over one season, which shifts livestock foraging decisions from preferred plants to the recently burned patch. As a result, intensified grazing on the patch can reduce exotic and invasive rangeland species (Cummings et al. 2007; Delaney et al. 2016). Furthermore, fire may release native plants from the inhibiting effect of thatch accumulations with bluegrass invasion (Kral et al. 2018; Toledo et al. 2014).

The sight of a blackened landscape suggests why livestock producers may perceive fire as destructive and expect reduced livestock production. However, regrowth following fire is highly nutritious (McGranahan et al. 2014), which can actually maintain or even improve livestock weight gains (Limb et al. 2011b). Unburned areas in patch-burn grazed pastures also provide a buffer when drought limits forage production in the burned patch (McGranahan et al. 2014). Therefore, patch-burn grazing may also be sustainable for livestock production in bluegrass-invaded pastures of the northern Great Plains.

Although we cannot eradicate Kentucky bluegrass from northern Great Plains rangelands, patch-burn grazing offers a low-cost solution that has the potential to not only control bluegrass but also promote native plant species that aid in the maintenance of forage production for livestock. Despite the advantages of prescribed fire for Great Plains rangelands, many private land managers suppress fire and avoid it for liability concerns (Yoder et al. 2004). Furthermore, most states have no incentives or regulations in place to protect burners (Wonkka et al. 2015). If bluegrass invasion remains unchecked, forage production has the potential to crash with extended periods of drought and leave livestock producers scrambling for adequate feed to support livestock. The importance of fire for the Great Plains is recognized, but needs to be treated as a natural process, like grazing, on the landscape. If we wait to test and implement alternative management strategies in the face of pervasive invasive species like bluegrass, there may be little biodiversity left to conserve.

Fire may be a useful tool in fighting bluegrass dominance, but the effects of bluegrass invasion on fire behavior remain unknown. Studies in pine forest systems have concluded that duff, or litter, thickness and moisture content are critical determinants of fuel combustion and level of consumption (Brown et al. 1991; Ferguson et al. 2002). Moisture content, especially, is a critical determinant of fire ignition and propagation as it acts as a heat sink in both live and dead fuels (Livingston and Varner 2016). Therefore, increased moisture can inhibit combustion through its evaporation and cooling of the flame (Chuvieco et al. 2004; Livingston and Varner

2016). Bluegrass thatch contains large-pores that may be capable of holding water (Toledo et al. 2014) which could increase the fuel moisture content of bluegrass-invaded prairies. Additionally, changes in fuel architecture or arrangement can alter fuel combustion and consumption (Mack and D'Antonio 1998; Wang et al. 2016). For example, exotic understory shrub invasions in forested ecosystems increase vertical continuity of the fuel bed and are known to increase or reduce flammability under drought and wet conditions, respectively (Varner et al. 2005; Wang et al. 2016). Bluegrass thatch visually appears to alter vertical fuel arrangement but there's no evidence to confirm that it does or to show how this may influence fire behavior in a grassland ecosystem. Increasing our understanding of the effects of invasive species, like bluegrass, on fuel characteristics and fire behavior is necessary to improve fire prescriptions and enhance the ability to achieve specific goals with fire management.

The purpose of this research was to provide evidence supporting and informing alternative management practices in bluegrass-invaded rangelands of the northern Great Plains. First, we compared the influence of traditional season-long grazing and alternative grazing management strategies early-intensive and patch-burn grazing on plant community dynamics of bluegrass-dominated sites. Alternative grazing management strategies reduced bluegrass dominance while traditional management increased it. Furthermore, we found that restoring the fire and grazing interaction is a viable option for livestock production in bluegrass-invaded systems as it does not reduce forage production, has the potential to enhance the consistency of production across years (McGranahan et al. 2016), and may sustain or enhance livestock production (Limb et al. 2011b). Second, we quantified fuel characteristics of a bluegrass-invaded fuel bed to inform prescribed fire management. We found that thatch in bluegrass-invaded systems is likely altering the fuel structure and moisture dynamics of northern Great Plains fuel beds, which may affect the ability of prescribed fire management to reduce the inhibiting effects of bluegrass thatch under certain environmental conditions. Thus, North American fuel models may need to adapt to consider thatch characteristics to increase the predictive accuracy of fire behavior models and, ultimately, improve the application and success of prescribed fire on bluegrass-invaded landscapes. Our research emphasizes the need for research on and improvements of alternative management strategies to conserve biodiversity and valuable ecosystem services in novel ecosystems.

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CHAPTER 1: ALTERNATIVE GRAZING MANAGEMENT STRATEGIES COMBAT INVASIVE GRASS DOMINANCE

Abstract

Biodiversity and ecosystem service conservation requires understanding the influence of management practices on ecosystem dynamics. Biological invasions in working landscapes can impair valuable services like forage production for livestock and create novel ecosystems with no historic reference to guide current management. Kentucky bluegrass (*Poa pratensis*; hereafter bluegrass) invasion in the northern Great Plains is actively displacing native species and traditional season-long (SL) grazing management can increase its abundance. Thus, we conducted a field experiment to determine if alternative grazing management practices, early-intensive (EI) and patch-burn (PB) grazing, influence plant community dynamics differently than traditional grazing management in bluegrass-invaded pastures. EI grazing involved triple stock density for the first third of the season while PB grazing incorporated SL stocking and a prescribed burn of one fourth of each pasture annually. We randomly assigned treatments to nine approximately 16-ha pastures (n = 3) with similar moderate stocking rates. Over three growing seasons, we conducted vegetation cover surveys and collected aboveground biomass samples to compare plant community dynamics and production among treatments. Although plant species dynamics (richness, evenness, Simpson's diversity) were not different among treatments, multivariate analyses revealed that plant community composition differed between traditional and alternative strategies after four years of treatment. Specifically, pastures treated with alternative practices had roughly 18 to 21% less bluegrass cover than traditional pastures at the study's end. Management strategy also did not differentially influence aboveground biomass production or the cover of the two most dominant native cool-season grasses. Although specifics

require further investigation, our results provide evidence for livestock producers to transition away from traditional SL grazing to control bluegrass invasion and mitigate its deleterious effects with alternative grazing strategies. Thus, this study reinforces the value of research exploring alternative management strategies for the conservation of biodiversity and ecosystem services in novel ecosystems.

Introduction

Directly and indirectly, human actions are causing the degradation of ecosystems across the globe (Cardinale et al. 2012). Habitat loss, land fragmentation, altered disturbance regimes, and exotic species invasions are disrupting numerous ecosystems (WWF 2016). Climate change is also threatening ecosystem integrity through alterations to growing season length and precipitation patterns (Alexander et al. 2006). These factors, among others, interact and have synergistic effects resulting in positive feedbacks with negative consequences for ecosystems and society (Cardinale et al. 2012). The most deleterious result of these and other ecosystem threats is likely the dramatic decline of global biodiversity (WWF 2016), which is fundamental for the maintenance of ecosystems and the provisioning of ecosystem services like food production (Hammond 1995). It is imperative that research investigates mechanisms driving biodiversity loss and their interactions with other ecosystem threats to reveal avenues that can mitigate losses and maintain ecosystem services.

Biodiversity declines may be particularly detrimental for grasslands of the North American Great Plains where human actions have reduced areas of native prairie by as much as 99.9% (Samson et al. 2004). Prior to European establishment, fire and grazing interacted synergistically with climate to shape Great Plains ecosystems (Fuhlendorf and Engle 2004; Samson et al. 2004). Land fragmentation, fire suppression, overgrazing, and invasive species currently threaten the integrity of remaining native prairies (Briske et al. 2008; D'Antonio and Vitousek 1992; Toledo et al. 2014). Past and current land management practices have further increased the vulnerability of grasslands to ecosystem threats, especially invasive species (Briske et al. 2008; D'Antonio and Vitousek 1992; Toledo et al. 2014). Consequently, biological invasions are one of the leading anthropogenic threats to biodiversity and are considered an important component of global change (Vitousek et al. 1997; WWF 2016).

Kentucky bluegrass (*Poa pratensis*; hereafter bluegrass) invasion is actively altering grassland ecosystems in the northern Great Plains (Toledo et al. 2014). Increased bluegrass abundance (Miles and Knops 2009) is threatening the biodiversity of grasslands by reducing the abundance of native plant species (Cully et al. 2003). Evidence suggests that its expansion over the last thirty years may be a response to the combination of multiple factors including outdated land management strategies, alterations to historic fire regimes, and increases in growing season length, atmospheric CO_2 concentrations, and average precipitation (DeKeyser et al. 2015; Toledo et al. 2014). Its origin in the United States is not clear (Carrier et al. 1916), but bluegrass was not a part of the region's historic plant community (Barker 1986) and was likely introduced to the region in the 1800s (DeKeyser et al. 2015). Furthermore, the USDA lists bluegrass as a naturalized, invasive species throughout the tallgrass, mixed-grass, and shortgrass prairie ecoregions (USDA-NRCS 2018). Bluegrass is a cool-season perennial grass that begins growth in early spring before the native cool-season species that dominate northern Great Plains grasslands. It also develops a dense root and thatch layer that restricts the establishment and growth of other species (Pierson et al. 2002; Toledo et al. 2014) by reducing light penetration of the understory and altering surface hydrology (Taylor and Blake 1982), soil structure (Herrick et al. 2001), and nutrient cycling (Badra et al. 2005). Ecosystem alterations resulting from bluegrass invasion have developed novel ecosystems throughout most of the northern Great Plains that may be irreversible (Toledo et al. 2014).

The development of novel bluegrass-invaded grasslands in the northern Great Plains has gone unnoticed likely because bluegrass provides adequate forage for livestock production, especially during early spring and wet years (Toledo et al. 2014). The forage value of bluegrass drastically declines when heat and water stress of the summer months or periods of drought induce dormancy (Hockensmith et al. 1997) and these periods are projected to increase in length as precipitation timing shifts under future climate scenarios (Alexander et al. 2006; Deguines et al. 2017). Thus, bluegrass dominance may leave the forage supply susceptible to climate change within and across seasons whereas a diverse community would provide adequate forage across a wider range of conditions. Grasslands managed for livestock production utilize strategic livestock grazing that traditionally promotes uniform distribution and forage utilization (Fuhlendorf and Engle 2001, 2004) such as season-long or rotational grazing (Bailey et al. 1998). Uniform disturbances simplify plant community composition across the landscape, as they do not allow the development of areas with varying levels of disturbance intensity or frequency (Bailey et al. 1998; Fuhlendorf and Engle, 2004). Bluegrass increases under season-long grazing (Cully et al. 2003; Murphy and Grant 2005; Smith and Owensby 1978) implying that its invasion expands under uniform disturbance regimes. Combatting bluegrass invasion will require a change in grazing management practices in the northern Great Plains.

At this time, there is a lack of empirical evidence to suggest effective grazing management strategies for bluegrass control. The northern Great Plains is a fire-adapted system that is resilient to grazing after burning (Gates et al. 2017; Powell et al. 2018; Strong et al. 2013; Vermeire et al. 2011), but it remains unclear how bluegrass responds to grazing after burning.

Therefore, we designed a study to characterize and compare how traditional season-long (SL) grazing and two alternative grazing management strategies influence vegetation dynamics of bluegrass-invaded mixed-grass pastures in the northern Great Plains. The first alternative grazing management strategy we chose to investigate was early-intensive (EI) grazing, which involves high intensity grazing during early spring. EI grazing can stabilize or decrease bluegrass populations in warm-season prairie (Smith and Owensby 1978) and may reduce its productivity (Bryan et al. 2000). Patch-burn (PB) grazing was the second alternative strategy we chose to investigate. The influence of both grazing and fire on the evolution of Great Plains grassland ecosystem is widely recognized (Fuhlendorf et al. 2009; Samson et al. 2004) and PB grazing management can promote structural and compositional diversity (Fuhlendorf and Engle 2001, 2004; Powell et al. 2018). Studies in the tallgrass (Anderson et al. 1970; Owensby and Smith 1979; Smith and Knapp 1999) and mixed-grass (Bahm et al. 2011; Engle and Bultsma 1984; Kral et al. 2018) prairie ecoregions indicate that burning can decrease bluegrass. However, the benefits of burning bluegrass are highly dependent on precipitation and soil type (Engle and Bultsma 1984) and reductions in mixed-grass prairie are short-term (Bahm et al. 2011; Kral et al. 2018). Analyzing the effects of grazing after prescribed burning, therefore, is relevant to determine if it can provide effective bluegrass control over multiple years.

The consequences of bluegrass invasion remain largely unknown for northern Great Plains ecosystems and are highly speculative (Toledo et al. 2014). Therefore, investigating how bluegrass-invaded communities respond to management is necessary to identify sustainable control mechanisms and quantify differences that can help improve the management of these novel ecosystems. In our study, we hypothesized that traditional (SL) and alternative grazing management strategies (EI and PB) would generate differences in plant community dynamics, composition, and bluegrass cover. Because native Great Plains plants evolved with fire and grazing (Samson et al. 2004), we also hypothesized that management strategies would increase or maintain the cover of native cool-season grasses without reducing aboveground biomass production. To address these hypotheses, our specific objectives were to quantify the influence of each grazing management strategy on plant community dynamics, community composition, bluegrass cover, cover of the two most dominant native cool-season grasses, and annual aboveground biomass production. Improving our understanding of how different land management strategies influence invaded ecosystems can elucidate ways to conserve biodiversity and simultaneously maintain essential ecosystem services in the face of increasing global change.

Methods

Site Description

Our field experiment took place at the North Dakota State University (NDSU) Central Grasslands Research Extension Center (CGREC) located near Streeter, North Dakota, USA (46°44'N, 99°27'W). The center lies within the Missouri Coteau ecoregion and the region's vegetation is representative of mixed-grass prairie dominated by green needlegrass (*Nassella viridula*) and western wheatgrass (*Pascopyrum smithii*), both native cool-season grass species. Non-native cool-season grasses Kentucky bluegrass (*Poa pratensis*) and smooth brome (*Bromus inermis*) as well as the native shrub western snowberry (*Symphoricarpos occidentalis*) are important drivers of biodiversity changes and currently dominate the area's rangelands (Limb et al. 2018).

This area has a continental climate with the average coldest temperature (-17°C) occurring in January and the warmest (27°C) occurring in July and August. Mean annual precipitation is 468-mm and about 70% falls between May and September (NDAWN 2018). Total annual precipitation was near average the year before sampling began and for the first sampling year (Fig. 1.1a). Total precipitation in 2016 was 137% of the 30-yr average and was below average (81% of the 30-yr average) in 2017 (NDAWN 2018). The most influential precipitation falls between May and June in North Dakota (Wiles et al. 2011) and was 108%, 169%, 83%, and 98% of the 30-yr average in 2014, 2015, 2016, and 2017, respectively (Fig. 1.1b). The regional average of 122 frost-free days allows the growth of both cool-season and warm-season plant species. Fine-loamy mollisols and irregular rolling plains dominate the region from the collapse of "superglacial" sediment (Bluemle 1991). We conducted our study on a site managed with a short-duration rotational grazing system for the previous 25 years (Kirby et al. 1986).

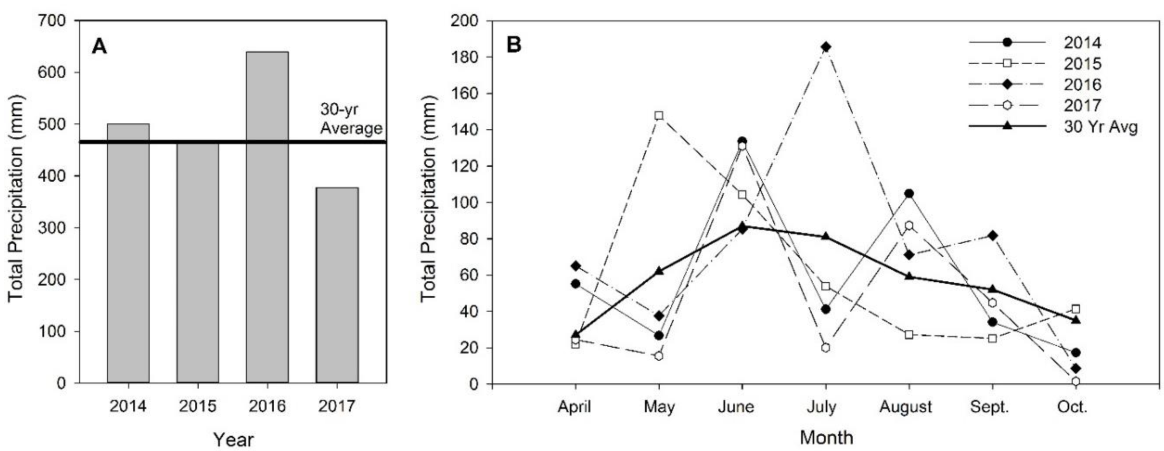

Figure 1.1. Precipitation in Streeter, ND, for 2014 through 2017. Total annual precipitation (A) and total monthly precipitation for each growing season (B) in Streeter, ND, USA for 2014 through 2017. Weather data acquired at the STREETER 7 NW, ND US USC00328415 station (46.7154ºN, -99.4475ºW) and retrieved from the National Environmental Satellite, Data, and Information Service of the National Oceanic and Atmospheric Administration (NOAA 2018). Thirty-year monthly averages for Streeter, ND, retrieved from the North Dakota Agricultural Network (NDAWN 2018).

Experimental Design

We initiated a completely randomized design experiment on nine approximately 16-ha bluegrass-invaded pastures with three treatments each replicated three times in 2014. Treatments followed traditional and alternative grazing management strategies to compare their influence on vegetation dynamics. Each grazing treatment incorporated a moderate stocking rate with yearling mixed-breed heifers on three pastures (n = 3). We stocked each pasture with the same animal unit months (1.85 AUM/ha) since all were similar in carrying capacity. Grazing treatments and cattle did not rotate among pastures within or across years. Fencing existed only on the exterior boundary of each pasture to allow cattle to make their own foraging decisions.

Grazing treatments emulated practices typical of, or alternative to, the study region. Traditional grazing management involves stocking pastures for the duration of the growing season. Thus, we stocked pastures in early-May for 12-weeks to establish a season-long (SL) grazing treatment. Our alternative grazing management treatments consisted of early-intensive (EI) and patch-burn (PB) grazing. EI grazing involved stocking pastures at triple stock density for the first third of the growing season (4-weeks early-May to early-June). PB grazing combined the SL grazing strategy with a prescribed fire regime. We burned a different fourth (approximately 4-ha) of each PB grazed pasture annually after a hard frost using a ring-fire technique on cured fuels with the first fire in October 2014. Therefore, each fourth of the PB pastures had a different time-since-fire at the fourth growing season, 2017. Weather conditions for burn operations were generally 50-70^{o}C with wind speeds <10 km/h and relative humidity between 40-60%.

Data Collection

We standardized sampling intensity among pastures by arbitrarily dividing each pasture into four equal patches based on the PB treatment. Data from 2014 revealed that plant community dynamics and composition were not different among treatments at the study's initiation ($p > 0.05$, data not shown). Thus, experimental plant community surveys occurred between late July and early August to monitor for changes among treatments in 2015, 2016, and 2017. Surveys involved estimating canopy cover of all vascular plants in each patch along a 40-m transect for a total of 4 transects per pasture. We stratified transects randomly on loamy ecological sites and recorded canopy cover from 0.5 x 0.5-m quadrats placed every 2-m. We identified all plants to species or family and recorded their canopy cover using a modified Daubenmire cover class system (1=trace-1%, 2=1-2%, 3=2-5%, 4=5-10%, 5=10-20%, 6=20-30%, 7=30-40%, 8=40-50%, 9=50-60%, 10=60-70%, 11=70-80%, 12=80-90%, 13=90-95%, 14=95-98%, 15=98-99%, 16=99-100%) (Daubenmire 1959). We converted cover classes to midpoint values for statistical analyses. Plant nomenclature, status, and distribution followed the USDA National Plant Database (USDA-NRCS 2018). Aboveground biomass production sampling occurred during peak production (mid-July) within three 2 x 2-m caged grazing exclosures randomly stratified each year on loamy ecological sites within each patch. We clipped all standing biomass to the soil surface from one random 0.5 x 0.5-m quadrat within each exclosure. Samples were oven dried at 150ºC to constant weight.

Statistical Analyses

We determined mean species richness, evenness, and diversity (Simpson's diversity D' = $1/\sum p_i^2$ where p_i refers to the proportion of each species i to the total number of species) for each pasture to analyze treatment effects ($n = 3$). We evaluated 2015 and 2016 means as trends and only tested for differences among treatment means in 2017 to allow the full implementation of the PB treatment when time-since-fire differed for each of the four patches. We used multivariate analysis to investigate changes in plant community composition across years and treatments. To test for treatment effects, year effects, and year × treatment interactions on plant community composition, we used permutation-based nonparametric multivariate analysis of variance (perMANOVA) with the Sorenson (Bray-Curtis) distance measure and pasture as the experimental unit. We used non-metric multidimensional scaling (NMS) procedures in PC-ORD 6.0 with the Sorenson (Bray-Curtis) distance measure in autopilot mode to determine the best-fit (lowest stress) in a possible one to six dimensional solution (McCune and Mefford 2011). Ordination scores for plant species revealed relationships to ordination axes. We used the same multivariate analyses on 2017 community composition data separately to investigate specific differences after full treatment implementation. We also compared 2017 ordination scores and mean canopy cover of bluegrass and native cool-season grasses, green needlegrass and western wheatgrass, to investigate differences among treatments. Finally, we tested for treatment effects on aboveground biomass production in 2017. All univariate data was analyzed with ANOVA procedures and post hoc Tukey's B means separation in the IBM-SPSS Statistics software package (Version 25; IBM Corp.).

Results

We recorded 123 plant species throughout the course of the study among all grazing treatments. Grazing treatments did not differ in species richness, evenness, or diversity at the end of the study ($p > 0.05$) (Fig. 1.2). Conversely, the perMANOVA analysis of plant community composition across all years and grazing treatments revealed a significant effect for year ($p < 0.001$), treatment ($p = 0.013$), and the year × treatment interaction ($p = 0.049$). Likewise, the

NMS analysis was useful (stress = 6.74) and resulted in a 2-dimensional solution (Fig. 1.3). Axis 1 explained 89.4% of the variability while axis 2 explained 7.4% (96.8% cumulative). Centroids were oriented along the primary axis according to year (Fig. 1.3a) and the secondary axis according to grazing treatment suggesting that year had a stronger influence than treatment on community composition (Fig. 1.3a). Plant community composition was similar among all grazing treatments in 2015 and 2016 while alternative and traditional management strategies differed in community composition in 2017 (Fig. 1.3a). Accordingly, the perMANOVA analysis on 2017 community composition revealed a significant treatment effect (p = 0.01) and the NMS ordination was useful (stress = 0.00011) with a single dimensional solution explaining 85% of the variability. Thus, our NMS and perMANOVA results indicate that plant community composition shifted over time according to both year and treatment (Fig. 1.3b) even though richness, evenness, and diversity did not.

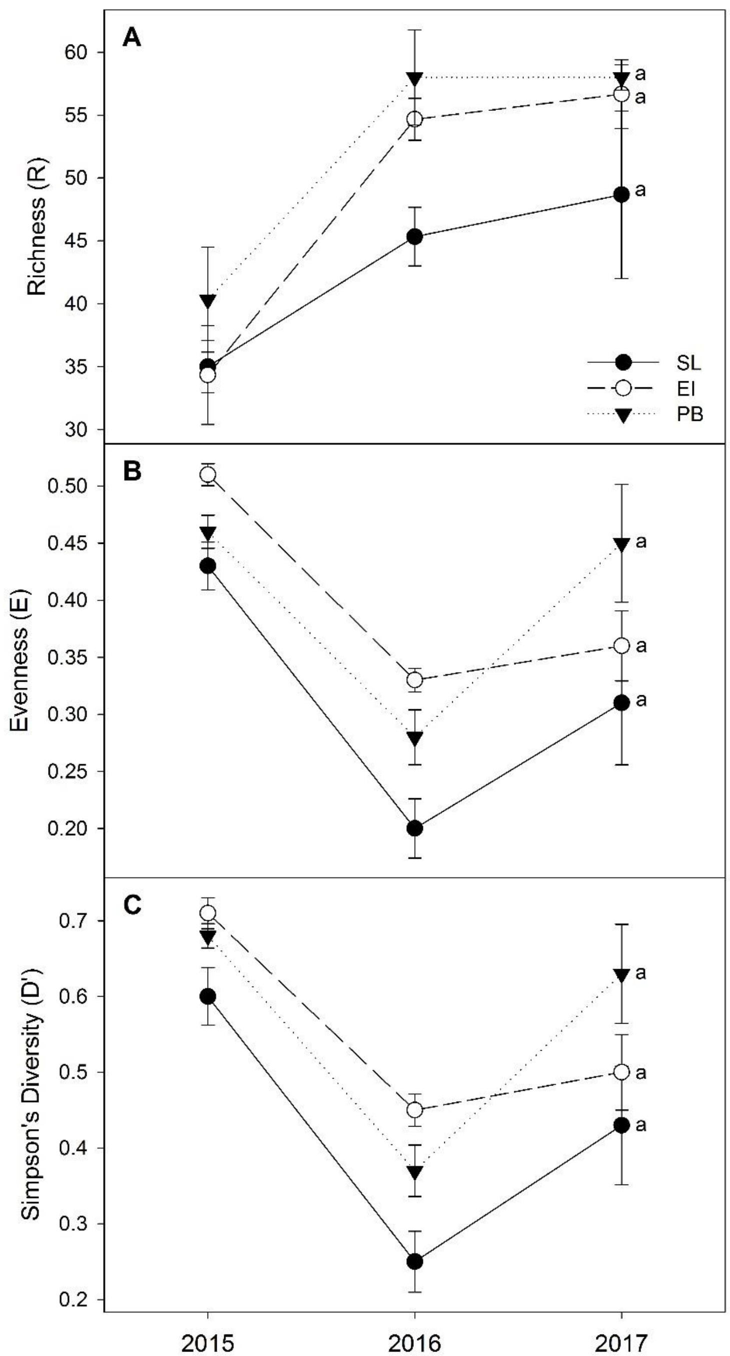

Figure 1.2. Summary statistics of plant community dynamics. Richness (A), evenness (B), and Simpson's Diversity (C) averages for pastures (n = 3) treated with season-long (SL), early-intensive (EI), and patch-burn (PB) grazing from 2015 through 2017 at the North Dakota State University Central Grasslands Research Extension Center near Streeter, ND. Different scaling among graphs. Letters (a,b,c) represent statistical differences among grazing treatments in 2017 ($p \leq 0.05$). Error bars represent standard error of the mean.

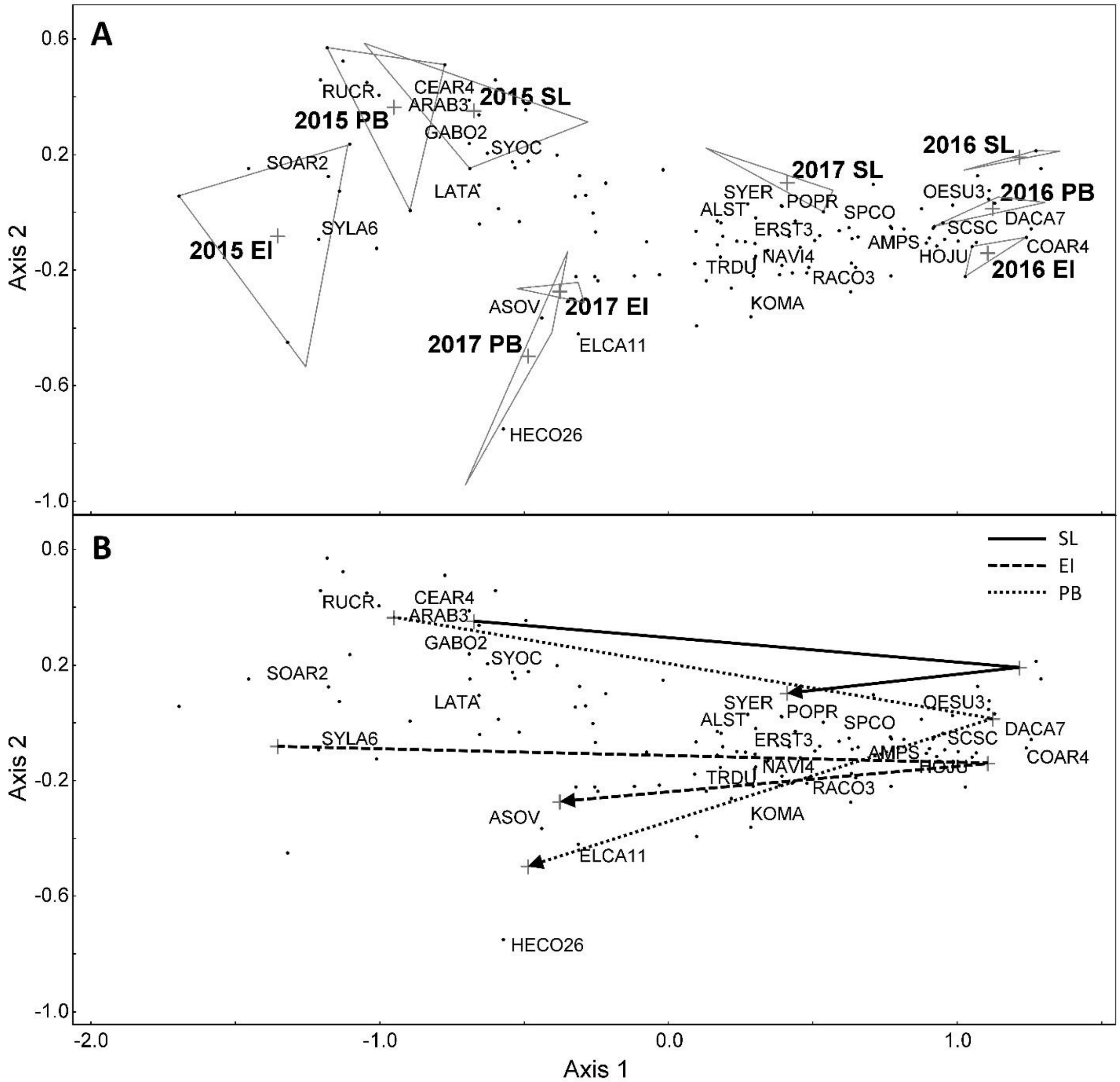

Figure 1.3. Non-metric multidimensional scaling (NMS) ordination of plant community composition with all species found across all years. NMS ordination for plant community composition data collected from 2015 through 2017 for pastures treated with season-long (SL), early-intensive (EI), and patch-burn (PB) grazing (*n* = 3) at the North Dakota State University Central Grasslands Research Extension Center near Streeter, ND. Convex hulls represent each treatment by year (A) while cross hairs indicate treatment by year average species composition. Vectors (B) represent the trajectory of changes in plant community composition over time for each grazing treatment across study years. Greater separation of convex hulls suggests greater plant community differences while less separation implies greater similarities. Points represent individual plant species. Species shown include the 5 strongest positive, 5 most negative, and the 5 central species for each axis. Plant species are labeled according to USDA Plants Database symbols and are defined in Table 1.1.

Table 1.1. Plant species correlation coefficients. Axis 1 and 2 correlation coefficients for each plant species shown in Figure 1.3 calculated with Sorenson (Bray-Curtis) distances in the non-metric multidimensional scaling (NMS) ordination of plant community composition of pastures treated with season-long, early-intensive, and patch-burn grazing at the North Dakota State University Central Grasslands Research Extension Center near Streeter, ND across 2015, 2016, and 2017 growing seasons.

Symbol	Scientific name	Growth Form*	Native / Introduced**	Axis 1	Axis 2
ALST	*Allium stellatum*	F	N	0.12	-0.07
AMPS	*Ambrosia psilostachya*	F	N	0.62	-0.19
ARAB3	*Artemisia absinthium*	F/S	I	-0.33	0.48
ASOV	*Asclepias ovalifolia*	F	N	-0.24	-0.58
CEAR4	*Cerastium arvense*	F	B	-0.37	0.59
COAR4	*Convolvulus arvensis*	F/V	I	0.22	-0.07
DACA7	*Dalea candida*	F/S	N	0.22	-0.07
ELCA11	*Elymus caninus*	G	I	-0.17	-0.63
ERST3	*Erigeron strigosus*	F	N	0.11	-0.12
GABO2	*Galium boreale*	F/S	N	-0.53	0.49
HECO26	*Hesperostipa comata*	G	N	-0.16	-0.60
HOJU	*Hordeum jubatum*	G	N	0.22	-0.07
KOMA	*Koeleria macrantha*	G	N	0.10	-0.38
LATA	*Lactuca tatarica*	F	N	-0.65	0.26
NAVI4	*Nassella viridula*	G	N	0.25	-0.54
OESU3	*Oenothera suffrutescens*	F/S	N	0.56	-0.10
POPR	*Poa pratensis*	G	B	0.97	0.14
RACO3	*Ratibida columnifera*	F	N	0.45	-0.57
RUCR	*Rumex crispus*	F	I	-0.42	0.48
SCSC	*Schizachyrium scoparium*	G	N	0.51	-0.15
SOAR2	*Sonchus arvensis*	F	I	-0.54	0.15
SPCO	*Sphaeralcea coccinea*	F/S	N	0.11	0.00
SYER	*Symphyotrichum ericoides*	F	N	0.57	0.16
SYLA6	*Symphyotrichum lanceolatum*	F	N	-0.53	-0.12
SYOC	*Symphoricarpos occidentalis*	S	N	-0.71	0.58
TRDU	*Tragopogon dubius*	F	I	0.09	-0.46

Plant species symbols, nomenclature, growth form, and status follow the USDA Plants Database (USDA-NRCS 2018). *Growth form: F=Forb, G=Graminoid, S=Shrub/Subshrub, V=Vine **Native/Introduced: B=Both, I=Introduced, N=Native

We found bluegrass within every individual quadrat each year. Across all treatments and years, our NMS analysis revealed that bluegrass had a strong positive correlation with axis 1 (0.968) and a poor correlation with axis 2 (0.141) (Table 1.1). Thus, year primarily influenced bluegrass while grazing strategy exerted a secondary effect. The NMS analysis of 2017 revealed that bluegrass was strongly correlated with traditional management (-0.909) while green needlegrass (0.785) and western wheatgrass (0.727) were strongly correlated with alternative management strategies upon the full implementation of the PB treatment. Therefore, the trajectory of changes in plant community composition shifted toward bluegrass dominance with SL grazing and shifted away with alternative EI and PB grazing strategies (Fig. 1.3b). Likewise, absolute canopy cover of bluegrass differed among traditional and alternative grazing treatments in 2017 ($p = 0.003$). Mean bluegrass cover with alternative EI and PB grazing management was approximately 18 and 21% lower than the traditional SL grazing treatment mean (48%), respectively (Fig. 1.4a). Across years, trends reveal that bluegrass cover was highest for each individual treatment in 2016 when precipitation was above average (Fig. 1.1 and 1.4a). Interestingly, bluegrass cover in 2017 was similar to 2015 levels in PB and EI grazed pastures but was approximately 160% greater than 2015 levels in SL grazed pastures.

In contrast, grazing treatments did not differentially influence the canopy cover of the two most dominant native cool-season grasses and aboveground biomass production at the study's end. Canopy cover of green needlegrass ($p = 0.20$, Fig. 1.4b) and western wheatgrass ($p = 0.24$, Fig. 1.4c) did not differ among treatments in 2017. Aboveground biomass production followed the same trend (Fig. 1.5). Production was highest with above average (2016) and lowest with below-average (2017) annual precipitation (Fig. 1.1 and 1.5).

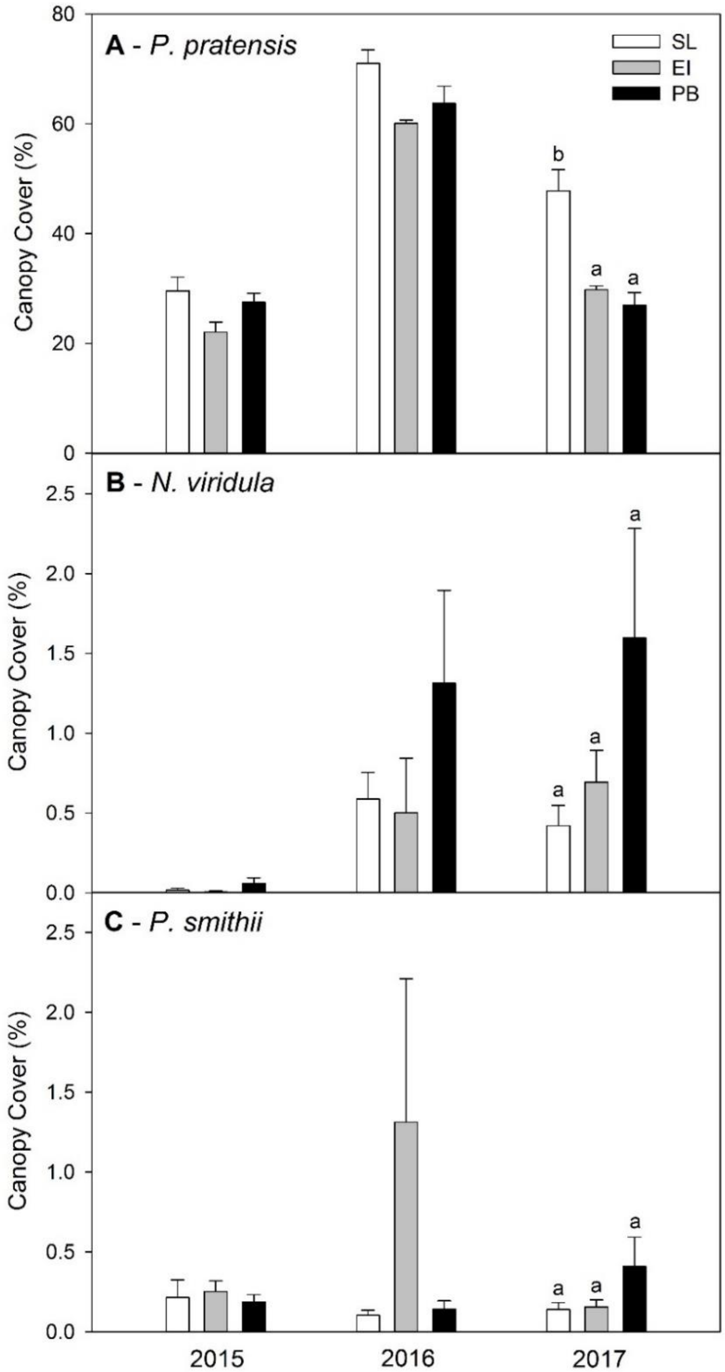

Figure 1.4. Canopy cover of invasive Kentucky bluegrass and the two most dominant native cool-season species, green needlegrass and western wheatgrass. Mean absolute canopy cover of Kentucky bluegrass (*P. pratensis*) (A), green needlegrass (*N. viridula*) (B), and western wheatgrass (*P. smithii*) (C) of pastures (n = 3) treated with season-long (SL), early-intensive (EI), and patch-burn (PB) grazing from 2015 through 2017 at the North Dakota State University Central Grasslands Research Extension Center near Streeter, ND. Different scaling among species graphs. Letters (a,b,c) represent statistical differences among grazing treatments in 2017 ($p \leq 0.05$). Error bars represent standard error of the mean.

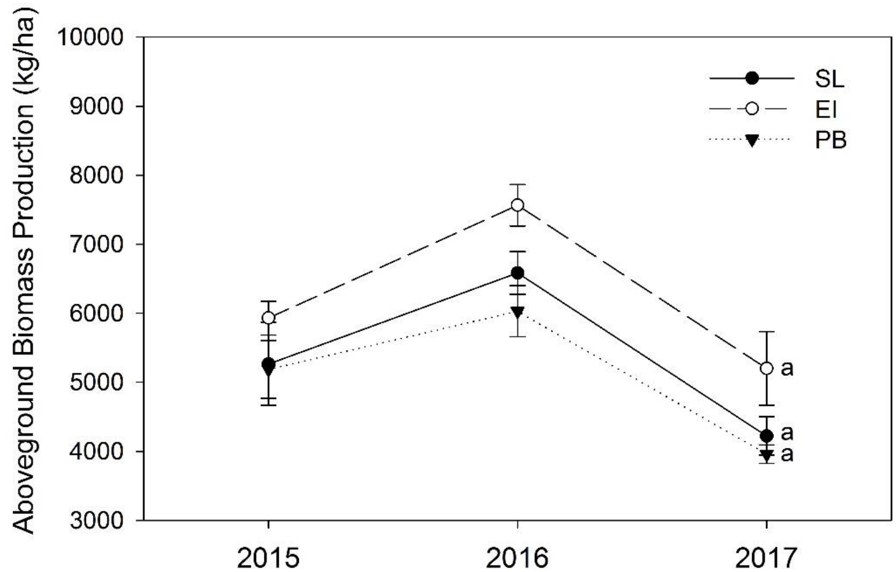

Figure 1.5. Annual aboveground biomass production. Mean annual aboveground biomass production of pastures treated with season-long (SL), early-intensive (EI), and patch-burn (PB) grazing (n = 3) from 2015 through 2017 at the North Dakota State University Central Grasslands Research Extension Center near Streeter, ND. Letters (a,b,c) represent statistical differences among grazing treatments in 2017 ($p \leq 0.05$). Error bars represent standard error of the mean.

Discussion

Achieving economic and biological objectives in novel ecosystems managed as working landscapes requires practices that bolster native species and mitigate the deleterious effects of invasive species (Hobbs 2007; Hobbs et al. 2009). Kentucky bluegrass invasion is actively developing novel ecosystems in northern Great Plains grasslands by creating a thickened thatch layer that displaces native species (DeKeyser et al. 2015; Ereth et al. 2017; Toledo et al. 2014). Ecosystem services like livestock production could suffer where bluegrass reduces the diversity and quality of forage resources (Hockensmith et al. 1997; Toledo et al. 2014). There is little evidence to recommend management practices that accomplish both economic and biological objectives in bluegrass-invaded systems. Research also has not investigated how bluegrass responds to grazing after prescribed burning. Therefore, we tested vegetation responses to traditional and alternative grazing management strategies in bluegrass-invaded pastures of the northern Great Plains. Our results suggest that community composition responds similarly for PB and EI grazing, which both become less similar to traditional SL grazed communities over time. Specifically, traditional management increased the influence of bluegrass on community composition while alternative management decreased its influence over time and increased the influence of other species including oval-leaf milkweed (*Asclepias ovalifolia*), bearded wheatgrass (*Elymus caninus*), and needle & thread (*Hesperostipa comata*). Although our multivariate analyses indicate that year-to-year variation likely exerted the largest influence, bluegrass cover increased with traditional management after three years while it returned to first year levels with both EI and PB grazing management. Moreover, prescribed burning maintained annual aboveground biomass production and prescribed burning followed by grazing maintained the cover of the two most dominant native cool-season grasses. Developing management strategies that maintain or increase native species will help promote biodiversity and maintain ecosystem services as bluegrass invasion alters ecosystem function and structure (Hobbs et al. 2009).

We did not observe differences among grazing strategies in plant community dynamics at the end of the study (Fig. 1.2), but we did see changes in community composition (Fig. 1.3). Patch contrast can take years to develop with PB grazing management (Moranz et al. 2012), so additional study years may be necessary to reveal notable shifts in community dynamics. Growing season precipitation drives grassland composition and production (Biondini et al. 1998; Deguines et al. 2017). Accordingly, shifts in plant community composition were influenced primarily by year-to-year variation with treatment having a secondary effect. Community composition changed the most for PB followed by EI grazing and least for SL grazing over time

(Fig. 1.3b). SL grazing increased the influence of bluegrass on community composition over time whereas EI and PB decreased it. Our study agrees with others that SL grazing increases bluegrass abundance (Fig. 1.4a) (Cully et al. 2003; Limb et al. 2018; Murphy and Grant 2005; Smith and Owensby 1978), which may have amplified its influence on plant community composition in our study. EI grazing reduces the early productivity of bluegrass (Bryan et al. 2000) and increased grazing intensity reduces the accumulation of dead biomass through increased levels of biomass removal and trampling (Biondini et al. 1998; Naeth et al. 1991). It is plausible that EI grazing reduced the influence of bluegrass by stunting its early growth and limiting its ability to establish a thickened thatch layer before the emergence of native species. Similarly, burning releases native plants from the inhibitory effects of bluegrass by removing accumulated thatch (Kral et al. 2018). Cattle preferentially graze recently burned areas for their increased palatability and nutritive value over non-burned areas thereby increasing grazing pressure in burned patches (Fuhlendorf and Engle 2004). Thus, we propose that prescribed burning followed by grazing not only removed existing thatch, but also may have limited the accumulation of thatch post-fire and released more later-emerging species from its inhibiting effects. Therefore, grazing after burning has the potential to extend the benefits of burning bluegrass by decreasing its influence on composition throughout the entire growing season. Further research should investigate how grazing management strategies influence bluegrass thatch and its relationship with plant community dynamics and composition.

Four years of treatment did not elicit differences among grazing treatments in the cover of green needlegrass and western wheatgrass at the end of the study (Fig. 1.4). Native mixed-grass prairie species evolved with variations in climate, fire, and grazing (Fuhlendorf and Engle 2001). Moreover, little bluestem (S*chizachyrium scoparium*), another native grass species, is known to increase with PB grazing management (Limbe et al. 2011a). Thus, we expected the cover of the most dominant native cool-season species, green needlegrass and western wheatgrass, would increase or remain unchanged by alternative strategies. Although not-significant, observed differences in their cover in 2017 warrants further investigation into the potential for them to increase over extended periods of time with PB grazing management.

Year-to-year variation strongly influenced bluegrass cover with treatment exerting a secondary influence over time (Fig. 1.3). Bluegrass allocates more resources to root than crown production and has a higher water potential uptake than both cool-season species (Dong et al. 2014). Thus, it is plausible that above average precipitation in 2016 elicited an increase in bluegrass cover in all treatments by increasing its rhizome production more than native species. Notably, bluegrass cover returned to first year levels under EI and PB grazing the following year while it remained high under SL grazing (Fig. 1.4a). Grazing during drought can reduce the growth potential and vigor of bluegrass (Dong et al. 2011, 2014). Thus, below average precipitation in 2017 may have provided a competitive advantage for native plants released from bluegrass inhibition with burning (Kral et al. 2018) and EI grazing (Biondini et al. 1998). Developing strategies that simultaneously promote natives and control invasive species is important for both biodiversity and ecosystem service conservation in novel ecosystems (Hobbs et al. 2009).

Our results also reveal that prescribed burning bluegrass-invaded mixed-grass range does not affect annual aboveground biomass production (Fig. 1.5). Year-to-year variation, likely yearly weather variation, exerted the strongest influence on aboveground biomass production as expected (Patton et al. 2007; Wiles et al. 2011). Research from the tallgrass prairie ecoregion suggests that increased spatial variability with fire and grazing management reduces the temporal variability of aboveground biomass production (McGranahan et al. 2016). Comparable results were not found in our study but observed differences among treatments in 2017 suggests that the effects of PB grazing on reducing the variability of aboveground biomass production warrants further investigation. The removal of senesced vegetation in burned patches may have enhanced re-growth in those areas while non-grazed unburned areas provided an aboveground biomass repository or "grass-bank" (McGranahan et al. 2014) during hot or dry periods that would reduce bluegrass productivity. Early growing season precipitation may influence forage availability during the timing of EI grazing management but our methods did not account for differences in seasonal production. Further research should investigate the impacts of patch burning on forage production over multiple years in bluegrass-invaded systems and the interaction of early-season precipitation with early-season forage production to inform EI grazing management.

Management Implications

The long-term sustainability of working landscapes is contingent on the conservation of biodiversity and the ecosystem services it supports (West 1993). Grasslands, where livestock production is a main objective, provide unique conservation opportunities as management practices can be adapted to address ecosystem threats at various scales, especially on private lands (Polasky et al. 2005; West 1993). Novel ecosystems pose a serious challenge for land managers as they may require modifications to management goals and practices (Hobbs 2007; Kirkman et al. 2013). An improved understanding of grazing management effects is necessary in the northern Great Plains where bluegrass has become the dominant species and created novel ecosystems with reduced diversity through the development of a thickened thatch layer (Toledo et al. 2014). Through a field experiment comparing traditional and alternative grazing management strategies, we found that alternative strategies generated differences in plant community composition and proved better options for achieving biodiversity objectives in novel bluegrass-invaded rangelands. Our results only represent one full cycle of the patch-burn treatment rather than multiple cycles as would occur in a livestock production setting. However, the lack of negative effects of alternative management and the increase of bluegrass with traditional management provide support for producers to transition away from traditional SL grazing management to alternative strategies in bluegrass-invaded landscapes. Specifically, alternative PB and EI grazing shifted plant community composition away from bluegrass indicating an increased influence or presence of native prairie species. Further research is necessary to determine if these strategies decrease the influence of bluegrass by releasing native plants from the inhibitory effects of thatch accumulation. Although yearly weather variations primarily influenced plant communities, our results suggest that altering grazing management strategies can elicit changes in composition in bluegrass-invaded landscapes.

The northern mixed-grass prairie is resilient to the interactions among fire and grazing and our results indicate that grazing followed by burning is suitable for promoting biodiversity and controlling the invasion of bluegrass. The lack of an influence of burning on annual aboveground biomass production and observed differences in variability support the premise that patch burning can increase consistency in aboveground production across years (McGranahan et al. 2016) which is vital as climate change alters precipitation patterns (Alexander et al. 2006; Deguines et al. 2017). Furthermore, PB grazing may stabilize livestock production (Allred et al. 2014). Cattle performance can respond similarly to SL grazing or improve with PB grazing (Limb et al. 2011b) and can decline with EI management in mixed-grass prairie (Grings et al. 2002). Therefore, we argue that restoration of the historic fire and grazing interaction has the potential to meet both biological and economic goals effectively in bluegrass-invaded rangelands. Prescribed burning followed by grazing may also extend the short-term benefits of burning bluegrass (Kral et al. 2018). Before research can recommend management practices for bluegrass invasion in the northern Great Plains, it is clear that we need to investigate their influence on livestock production and identify management specifics in bluegrass-invaded landscapes. As a whole, our study demonstrates that alternative management strategies may be necessary to control invasive species spread, conserve biodiversity, and maintain ecosystem services in invaded, working landscapes (Ereth et al. 2017).

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CHAPTER 2: FUEL CHARACTERISTICS ASSOCIATED WITH INVASIVE PERENNIAL GRASS IN A GRASSLAND ECOSYSTEM

Abstract

Planning prescribed burns requires understanding fuel characteristics to ensure fire behavior predictions align with management goals. Invasive species in fire-prone ecosystems can transform surface fuels and complicate prescribed fire management. Kentucky bluegrass (*Poa pratensis*; hereafter bluegrass) invasion in northern Great Plains prairies is developing novel ecosystems with a thickened thatch layer on the soil surface. Bluegrass thatch not only inhibits germination but also contains pores capable of holding water, and may be difficult to burn through to mineral soil. Fire can be used to control bluegrass invasion but management specifics are unclear. Thus, we conducted a field study to quantify fuel bed characteristics of an invaded idle pasture in North Dakota. We collected samples of bluegrass thatch and standing bluegrass fuels separately during the growing season across mesic and xeric conditions to determine if they express different characteristics. First, we tested fuels for differences in bulk density. Second, we compared fuel moisture content of both fuel sample types under differing environmental conditions. Lastly, we tested for relationships between moisture content and relative humidity for each fuel type on mesic and xeric days. Thatch was roughly two orders of magnitude more dense than standing bluegrass fuels. Furthermore, thatch was always drier than standing fuels and its moisture content was influenced by environmental conditions while standing fuels were not. Regression analysis suggested that standing bluegrass fuels dried faster than thatch as relative humidity declined on both mesic and xeric days. Thus, it is plausible that bluegrass thatch and standing bluegrass fuels elicit differences in fire behavior. Moreover, we argue that fuel particle distribution is not uniform with bluegrass invasion as surface fuel models assume. This study

suggests fire behavior models and prescribed fire management may require adjustments to increase prediction accuracy and the ability to achieve specific objectives, respectively.

Introduction

Frequent fires of varying intensity, scale, and origin formed and maintained North American rangelands (Axelrod 1985). Alterations to natural fire regimes since European establishment have reduced and simplified the face of rangeland ecosystems (Samson and Knopf 1994). Moreover, biodiversity and ecosystem services have declined where alterations have allowed exotic and woody plant invasions (Twidwell et al. 2016). Severe alterations have resulted in the emergence of novel ecosystems that have no historical precedent to guide management (Hobbs et al. 2009). Managers are increasingly recognizing the importance of fire management for biodiversity conservation, but many questions remain regarding specific effects and proper implementation (Driscoll et al. 2010; Kelly et al. 2015).

Prescribed fire is a cost-effective management tool that managers can use to impose a fire regime tailored to site characteristics and specific objectives (Kelly et al. 2015). Predicting fire behavior is necessary for safe and effective management (Johnson and Miyanishi 1995), so managers are increasingly using fire behavior models and simulations to plan prescribed burns. Computer simulations, like BehavePlus in the United States, are used to predict fire behavior, plan prescribed fires, and analyze wildfire risk among a variety of ecosystems (Andrews 2014). The Rothermel (1972) fire spread model is the most widely evaluated among all fire models and serves as the basis for BehavePlus (Pastor et al. 2003). Fire behavior models relate environmental parameters (e.g. fuel characteristics, landscape features, and weather conditions) to fire behavior characteristics (e.g. rate of spread, intensity, and fuel consumption) (Pastor et al. 2003). The prediction accuracy of fire models is improving with model revisions and customization options, but evidence suggests room for improvement remains (Cruz et al. 2018). The ecological effects of fire depend on fire behavior, so continual improvement of models is necessary to improve the predictions that dictate prescribed burn management.

Justifying and planning actions to manage novel ecosystems with prescribed fire is difficult without knowledge of the effects of invasive species on fuel characteristics. In North American rangelands, exotic grass invasions elicit changes in fire behavior by altering fuel bed characteristics like fuel load, continuity, and moisture content (D'Antonio and Vitousek 1992). Ignition probability and fire spread have increased in the shrub-steppe ecoregion of western North America where exotic annual cheatgrass (*Bromus tectorum*) invasion has increased both fuel load and continuity (D'Antonio and Vitousek 1992). Alterations to fuel moisture can also affect fire behavior with regard to fuel ignition, intensity, and spread (Livingston and Varner 2016). Invasive tall fescue (*Festuca arundinacea*) actively grows when native warm-season species are dormant in the tallgrass prairie ecoregion. Because fuel moistures acts as a heat sink limiting combustion in both live and dead fuels (Chuvieco et al. 2004), increased live fuels with high fuel moisture are reducing fire intensity and spread in tall fescue-invaded tallgrass prairie ecosystems (McGranahan et al. 2013). To our knowledge, research has not documented changes in fuel arrangement associated with exotic grass invasions in rangeland ecosystems. Understanding fuel alterations is important to improve fire behavior modelling and inform the theory and application of natural fire regime restoration.

Modelling of surface fire behavior may be inaccurate if an exotic grass invasion alters fuel arrangement in a grassland ecosystem because it would challenge the uniform particle distribution assumption of surface fuels (Pastor et al. 2003). The purpose of this study was to investigate Kentucky bluegrass (*Poa pratensis*; hereafter bluegrass) invasion in the northern

Great Plains as a model of an invasive grass potentially influencing surface fuel arrangement. Bluegrass is actively displacing native species and developing novel ecosystems across the region with the development of a dense root and thatch layer (Toledo et al. 2014). Thatch is a tightly interwoven layer of dead plant material that develops from an imbalance between production and decomposition (Murray and Juska 1977). Between the soil surface and plant canopy, thatch not only reduces light penetration of the understory, but also acts as a buffer that moderates environmental conditions experienced at the soil surface (Murray and Juska 1977). Differences in the vertical and horizontal structure of thatch layers between native mixed-grass and bluegrass-dominated rangelands of the northern Great Plains appear to be substantial but have not been quantified. Thus, bluegrass invasion provides a relevant case study to test for alterations in fuel arrangement in a grassland ecosystem. This information can help improve fire behavior predictions and enhance the restoration of natural fire regimes for biodiversity conservation in novel ecosystems.

Research on the use of fire in bluegrass-invaded landscapes is increasing but reductions in bluegrass cover with prescribed fire are short-term (Bahm et al. 2011; Kral et al. 2018) and dependent upon precipitation and soil type (Engle and Bultsma 1984). Investigating how bluegrass invasion influences surface fuel characteristics may inform these findings and improve prescribed fire management. Thus, we conducted a field study to quantify fuel characteristics in a bluegrass monoculture on idle rangeland with the aim to determine if the fuel characteristics of bluegrass thatch differ from standing bluegrass fuels. First, we compared bulk density of bluegrass thatch and standing bluegrass fuels to test for differences in fuel particle distribution. Next, we quantified the influence of mesic (wet) and xeric (dry) conditions on the fuel moisture of each fuel type to determine if they exhibit differences in moisture content. Our third objective was to quantify the influence of relative humidity on bluegrass thatch and standing bluegrass fuel moisture under mesic and xeric conditions to test for differences in moisture dynamics. Because it is unlikely to impossible that we can eradicate bluegrass from this system, improving methods to control or maintain low levels of bluegrass over time will be essential to preserve native plant diversity and ecosystem services (Toledo et al. 2014). Our findings will also aid in the improvement of fire behavior modelling to enhance the ability to achieve management objectives with prescribed fire.

Methods

Site Description

We quantified fuel bed characteristics in a bluegrass monoculture on idle rangeland at the North Dakota State University (NDSU) Central Grasslands Research Extension Center (CGREC) located near Streeter, North Dakota, USA (46^{o}44'N, 99^{o}27'W). Our study site falls within the Missouri Coteau ecoregion's mixed grass prairie. Green needlegrass (*Nassella viridula*) and western wheatgrass (*Pascopyrum smithii*) dominated the region's rangelands historically. Today, Kentucky bluegrass (*Poa pratensis*), smooth brome (*Bromus inermis*), and western snowberry (*Symphoricarpos occidentalis*) dominate most of the area's rangelands and are driving changes in biodiversity (Limb et al. 2018). The collapse of "superglacial" sediment imparted fine-loamy mollisols and irregular rolling plains across the region (Bluemle 1991). The region's continental climate is generally coldest in January and warmest in July and August. Mean annual precipitation is approximately 468-mm and the majority (approximately 70%) falls May through September (NDAWN 2018). Growing season precipitation during our study was 88% and 128% of the thirty-year average for 2017 and 2018, respectively (NDAWN 2018, NOAA 2018) (Fig. 2.1).

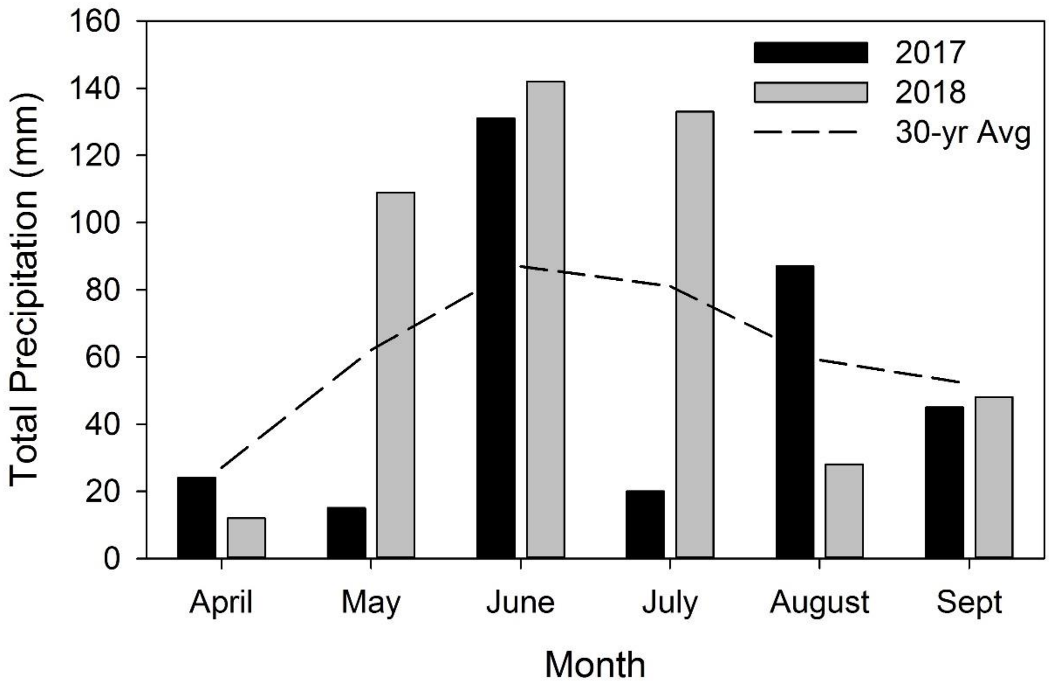

Figure 2.1. **Total monthly growing season precipitation for 2017 and 2018 in Streeter, ND.** Weather data acquired at the STREETER 7 NW, ND US USC00328415 station (46.7154°N, -99.4475°W) and retrieved from the National Environmental Satellite, Data, and Information Service of the National Oceanic and Atmospheric Administration (NOAA 2018). Dashed line represents the thirty-year average retrieved from the North Dakota Agricultural Network (NDAWN 2018).

Data Collection

We selected a 20 x 20-m fenced site excluded from grazing for the previous three years where bluegrass dominated community composition. On each of four different days, we collected bluegrass thatch and standing bluegrass fuels as separate fuel sample types. Fuels were sampled during mesic (wet) and xeric (dry) conditions during the growing season. We collected mesic samples immediately following precipitation events over 12.7-mm in total and xeric samples when the site received less than 12.7-mm total precipitation over the previous 72 hours. Data collection occurred on the following dates: 3 August 2017 (mesic), 27 May 2018 (xeric), 4 July 2018 (mesic), and 17 August 2018 (xeric). We retrieved all weather data from the Streeter (6NW) North Dakota Agricultural Weather Network station (NDAWN 2018). Sampling began either the hour of sunrise (xeric) or the hour after precipitation ceased (mesic) and ended the hour of sunset on each of the four sampling days. Grasses are classified as 1-hour fuels as they are under ¼ inch in diameter. Thus, we collected hourly samples because the moisture content of 1-hours fuels is expected to change hourly with corresponding changes in weather conditions, especially relative humidity (RH) (Rothermel 1972).

We sampled bluegrass thatch and standing bluegrass fuels separately each hour from 10 random points characterized by a bluegrass monoculture. At each point, we sampled standing bluegrass fuel by measuring the height of and clipping all aboveground biomass (including live and dead fuels) to the top of the thatch layer within a 10.8-cm diameter area. We then cut a 10.8-cm diameter thatch-fuel core from the same point, measured thatch depth, and separated thatch (including live and dead material) from the mineral soil. All samples were immediately placed in plastic bags, weighed, and oven dried at 150^{o}C for 48 h. Fuel sample types were considered independent as standing bluegrass fuels do not influence bluegrass thatch characteristics and vice versa at any given point in time.

Data Analyses

To accomplish our first objective, we calculated bulk density for each fuel sample type by dividing dry weight (g) by volume (cm^3, calculated as a cylinder with a 10.8-cm diameter and height determine by height of the respective sample). We measured bulk density because it influences the oxygen supply available for combustion and, therefore, can affect fire behavior (Rothermel 1972; Santoni et al. 2014). Bulk density measurements were averaged for each sampling day regardless of environmental conditions as moisture content has no influence on this measurement, so this analysis included four repetitions (n = 4). We tested for differences in the bulk density of bluegrass thatch and standing bluegrass fuels with one-way analysis of variance (ANOVA) procedures in the IBM-SPSS Statistics software package (Version 25; IBM Corp.).

Next, percent fuel moisture was determined for each fuel sample type with the following formula: [(wet weight – dry weight)/dry weight] × 100. Fuel moisture is influenced by environmental conditions while our second objective was to test for differences in fuel moisture content between bluegrass thatch and standing bluegrass fuels. Therefore, fuel moisture content for each fuel sample type was averaged within environmental conditions, so we analyzed two repetitions (n = 2) for samples collected on mesic and xeric days. We used ANOVA procedures and Tukey's B mean separation in the IBM-SPSS Statistics software package (Version 25; IBM Corp.) to compare averages across fuel sample types and conditions.

Finally, we used regression analysis to test for differences among fuel sample types in their relationships between fuel moisture content and RH on mesic and xeric days. All observations (10 samples of each fuel type collected hourly) were treated as independent samples as grasses are 1-hour fuels influence by hourly changes in RH and one sample type did not influence the characteristics of other. Hourly data collection was used to gather hourly RH values from the Streeter (6NW) North Dakota Agricultural Weather Network station (NDAWN 2018). We used regression analysis (Version 25; IBM Corp.) to determine the strength of the relationship (r^2) between relative humidity (RH) and fuel moisture for both bluegrass thatch and standing bluegrass fuels under mesic and xeric conditions. A significant regression slope indicated a relationship between fuel moisture (dependent variable) and RH (independent variable).

Results

ANOVA procedures revealed bulk density and moisture content differed between bluegrass thatch and standing bluegrass fuels. Bluegrass thatch had approximately 290 times the bulk density of standing bluegrass fuels ($p < 0.001$) (Fig. 2.2a). Moisture content differed between fuel types under both environmental conditions ($p < 0.001$) and the difference was more pronounced under xeric (34.11 ± 1.10%) than mesic conditions (15.53 ± 1.15%) ($p < 0.001$) (Fig. 2.2b). Mesic conditions resulted in higher bluegrass thatch moisture than xeric conditions while conditions (mesic or xeric) did not influence standing bluegrass fuel moisture (Fig. 2.2b).

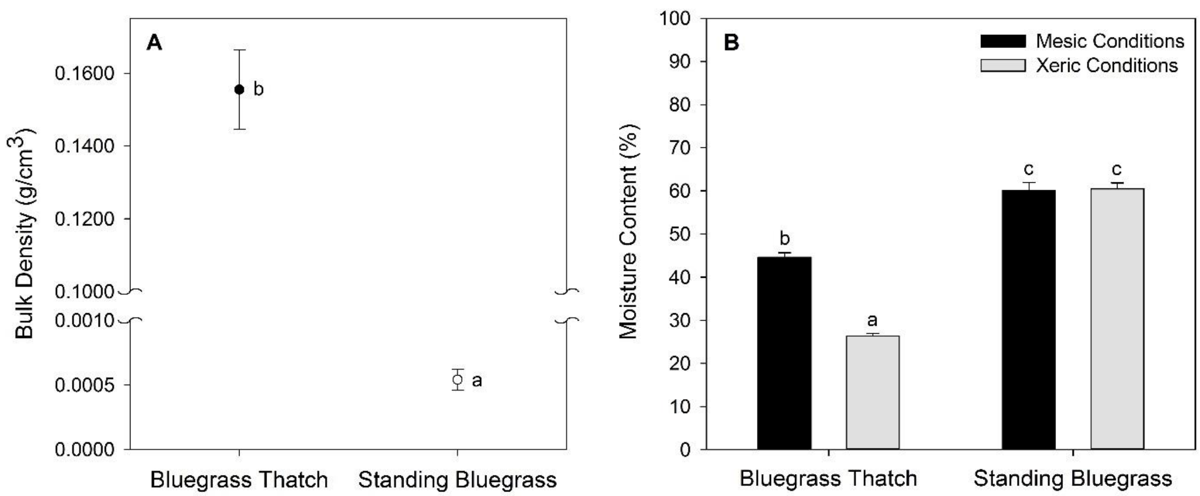

Figure 2.2. Bulk density and fuel moisture content of bluegrass thatch and standing bluegrass fuels. Bluegrass thatch and standing bluegrass fuel mean bulk density (g/cm^3, n=4 daily averages) (A) and moisture content (%) under mesic (wet, n=2 daily averages) and xeric (dry, n=2 daily averages) conditions (B) in a bluegrass monoculture at the North Dakota State University Central Grasslands Research Extension Center near Streeter, ND. Samples were collected from an idle site on four random days (n = 4) across the 2017 and 2018 growing seasons. Error bars represent standard error of the mean. Letters (a,b,c) represent statistical differences among means ($p \leq 0.05$). Figure 2.2a has a y-axis break from 0.001 to 0.1000 g/cm^3 and different scaling pre- and post-break.

The data revealed a positive relationship between fuel moisture content and RH for both bluegrass thatch and standing bluegrass fuels under mesic and xeric conditions (Fig. 2.3). Therefore, moisture content of both fuel types declined throughout the day as RH declined. The relationship was strongest for bluegrass thatch ($r^2 = 0.33$) and standing bluegrass fuel moisture ($r^2 = 0.34$) under mesic conditions (Fig. 2.3a). The data reveal a stronger influence of RH on standing fuel moisture than basal fuel moisture in both scenarios (Fig. 2.3b). Moreover, standing fuel moisture changed at a rate that was 187% and 420% that of bluegrass thatch under mesic and xeric conditions, respectively. Basal fuel moisture was nearly constant under xeric conditions (Fig. 2.3b).

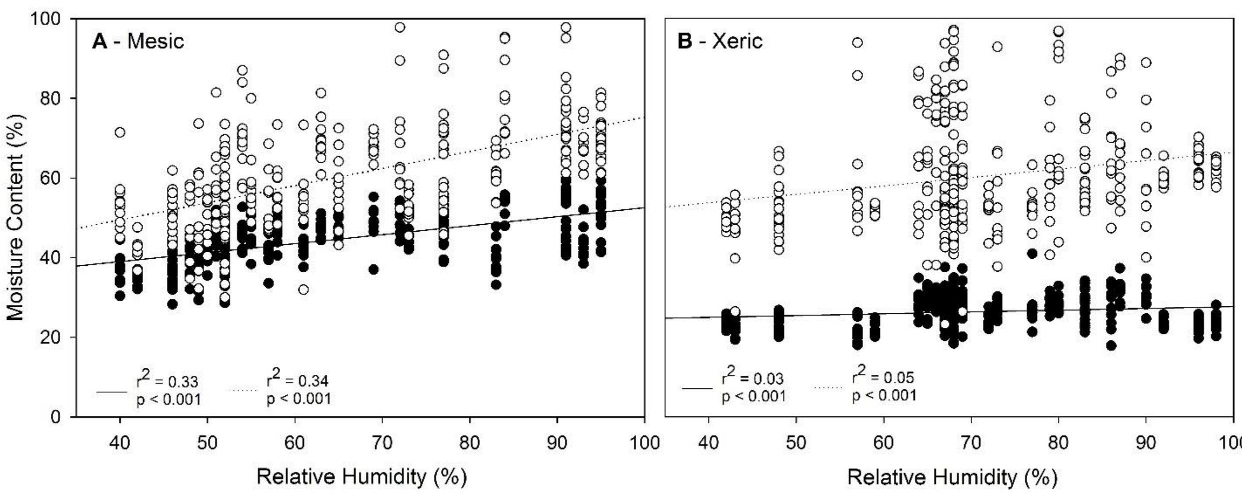

Figure 2.3. Fuel moisture content of bluegrass thatch and standing bluegrass fuels along a gradient of relative humidity (RH) in a bluegrass monoculture. Data collected at the North Dakota State University Central Grasslands Research Extension Center near Streeter, ND, under mesic (wet) conditions (A) and xeric (dry) conditions (B) during the growing season. Solid circles and solid lines represent bluegrass thatch while open circles and dashed lines represent standing bluegrass fuels (mesic, bluegrass thatch $y = 30 + 0.23x$; mesic, standing bluegrass $y = 32.31 + 0.43x$; xeric, bluegrass thatch $y = 12.17 + 0.05x$; xeric, standing bluegrass $y = 45.3 + 0.21x$).

Discussion

Effective restoration of fire regimes in fire-prone grassland ecosystems can aid efforts to control invasive species spread and maintain native biodiversity (Kelly et al. 2015). However, invasive species can complicate the success of prescribed burn management where they alter fuel bed characteristics (D'Antonio and Vitousek 1992; McGranahan et al. 2012). Fire behavior modeling can predict the effects of invasive species on fire behavior and inform prescribed fire management (Pastor et al. 2003). Bluegrass invasion in the northern Great Plains is developing a thickened thatch layer on the soil surface but research has not investigated its influence on fire behavior and prescribed fire management (Toledo et al. 2014). We conducted a field study to test for differences in fuel characteristics between bluegrass thatch and standing bluegrass fuels. Our results indicate that bluegrass thatch and standing bluegrass fuels differ in bulk density and represent separate fuel types. Moreover, both fuel types differed in moisture content regardless of environmental conditions and expressed different relationships with RH. Consequently, our results may be the first to suggest that an exotic grass invasion has the potential to alter fuel arrangement in a fire-prone grassland ecosystem.

We found that bluegrass thatch was roughly two orders of magnitude more dense than standing bluegrass fuels (Fig. 2.2a) indicating lower oxygen concentration for combustion in bluegrass thatch. North American surface fuel models assume that fuel particles are uniformly distributed throughout the fuel bed (Pastor et al. 2003; Rothermel 1972), but our findings provide no support for this assumption in idle bluegrass-invaded rangelands. Thus, we propose that bluegrass is likely altering fuel arrangement where it has invaded rangelands through the development of a thickened thatch layer. Fire spread declines as bulk density of a fuel bed increases while maximum temperature and burning time increase (Grootemaat et al. 2017). Percentage of fuel combustion also declines as fuels become more tightly packed (Gillon et al. 1995). Therefore, bluegrass thatch may burn slower and longer than standing bluegrass fuels and its combustion may be limited as its density increases. Consequently, we suggest that research considers the influence of bluegrass thatch density on combustion and consumption of the thatch layer and resulting impacts on bluegrass control. Identifying specific effects and control mechanisms is necessary to improve prescribed fire management for biodiversity conservation.

The moisture content of bluegrass thatch was always less than that of standing fuels regardless of environmental conditions (Fig. 2.2b). We also found that as RH declines throughout the day, the moisture content of standing bluegrass fuels declines nearly twice as fast as bluegrass thatch under mesic conditions (Fig. 2.3a). Moreover, RH had almost no influence on moisture content of bluegrass thatch during xeric conditions (Fig. 2.3b). Minor changes in fuel moisture can elicit drastic changes in fire behavior (Jolly 2007). Therefore, we propose that observed differences in moisture dynamics between bluegrass thatch and standing bluegrass fuels also have the potential to elicit differences in fire behavior characteristics in bluegrass-invaded rangelands. Furthermore, we found that bluegrass thatch holds more moisture under mesic than xeric conditions (Fig. 2.2b). Evidence suggests that thatch is highly porous but has little effect or an increasing effect on water infiltration in turfgrass systems (Taylor and Blake 1982). Thus, additional research is necessary to determine if our observed differences in fuel moisture have implications for infiltration as well as fuel combustion in northern Great Plains rangelands.

Management Implications

Fire behavior models are often used to plan prescribed burns and predict the effects of changes to fuel bed characteristics. Accurate predictions are necessary to ensure the safety and efficacy of fire management, but predictions from fire behavior models are not 100% accurate (Cruz et al. 2018). Consequently, constant improvement of models is valuable to improve prediction accuracy and prescribed burn management. North American models of surface fire behavior operate under the assumption that fuel particle distribution in surface fuels, including grassland fuels, is uniform throughout the fuel bed (Pastor et al. 2003; Rothermel 1972). Bluegrass thatch is substantially denser than standing bluegrass fuels, which suggests that fuel particle distribution is not always uniform in surface fuel beds. Consequently, our findings indicate that North American fuel models may need to address differences between thatch and standing fuels to improve prediction accuracy, especially in bluegrass-invaded rangelands.

The use of prescribed fire to manage North American grasslands is increasing and may aid in the control of invasive species (Kelly et al. 2015). However, the use of prescribed fire to control invasive species without understanding and improving specific control mechanisms is often ineffective (Foster et al. 2003). Research on the use of prescribed fire as a management tool for bluegrass invasion in the northern Great Plains indicates that it has the potential to control bluegrass but management specifics remain largely unknown and the success is often short-lived (Bahm et al. 2011; Engle and Bultsma 1984; Kral et al. 2018). Our results indicate that bluegrass invasion may be altering fire behavior through alterations to fuel arrangement and differences in moisture dynamics between bluegrass thatch and standing bluegrass fuels. For instance, bluegrass thatch may burn slower and longer than standing bluegrass fuels and the difference may be more pronounced during mesic conditions when fuel moisture declines slower for bluegrass thatch than standing fuels as RH decreases. Conducting prescribed burn management during the dormant or late growing season can reduce bluegrass cover without negatively affecting native species (Kral et al. 2018). It is likely that the fuel moisture content and moisture dynamics of bluegrass thatch and standing bluegrass fuels are more similar for senesced bluegrass, but research needs to evaluate relationships among fuel moisture and seasonality in bluegrass-invaded systems to reveal specific mechanisms. Moreover, research should compare fuel particle distribution among native and bluegrass-invaded rangelands to determine if bluegrass thatch is truly a novel fuel component. Determining how invasive species alter ecosystem properties, like fuel bed characteristics, will aid in developing management strategies that conserve biodiversity and maintain valuable ecosystem services. As a whole, our findings reinforce the value of improving fire behavior models and the importance of research on the effects of invasive species on fuel bed and fire behavior characteristics.

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