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Ecological Impacts of Restoring Fire-Grazing Interaction in Sandhills Prairie through Patch-Burn Grazing

By

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A Collaborative Adaptive Management (CAM) Project was started at the University of Nebraska in 2020 to address some of the key uncertainties related to the management of grasslands in the Nebraska Sandhills through stakeholder driven experiments and the adaptive management cycle. Patch-burn grazing was selected by CAM as a management tool to generate heterogeneity across the landscape and promote biodiversity while balancing economic and ecological trade-offs. The patch-burn grazing system was implemented with controlled burns in May of 2022 and March of 2023. Other parties in CAM will be examining the impact that patch-burn grazing has on forage and livestock performance, and early results show an increase in the weight gain of cattle in the patch-burn grazing system. The goal of the research presented here is to understand how the use of patch-burn grazing impacts several ecological aspects of the Nebraska Sandhills. Specifically, this study asks three things 1) does patch-burn grazing negatively impact soil conditions by increasing soil erosion and depleting the thin topsoil of nutrients in burned areas, 2) is patch-burn grazing able to significantly change vegetation structure and promote vegetation heterogeneity, and 3) how does patch-burn grazing affect avian communities, their species diversity, and abundance in the Sandhills? The comparison of soil conditions between burned and unburned was made using erosion pins installed throughout the burned and unburned fields and a series of soil nutrient panels samples taken before and, in the months following the fire. Vegetation structural metrics and function group covers were measured throughout each field in the study. A nonmetric multidimensional scaling (NMDS) ordinal analysis supported by a pairwise comparison using permutational multivariate analysis of variance (PERMNOVA) was used to examine the difference in vegetation structure between each of the fields in this study. Bird point counts were performed in each field throughout the two years of this study. This data was used to calculate and compare species diversity, community composition, and the abundance of a few select species. NMDS and PERMNOVA were used to explore the differences between the avian communities in each field, while *N-mixture* models were used to estimate abundance. Patch-burn grazing proves it is able to change the vegetation structure of the Nebraska Sandhills to promote heterogeneity and create more habitat for a diversity of different grassland bird species without compromising soil health. This study provides an understanding of how patch-burn grazing, an under-utilized tool in the Nebraska Sandhills, can be used to support a more heterogeneous and resilient grassland.

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Chapter 1-Introduction

The Nebraska Sandhills is a distinct ecoregion in the larger Great Plains region of North America that is characterized by semi-arid mixed grass prairies and rolling grass-stabilized sand dunes with some of the least fragmentation (Augustine et al. 2021). It is the world's most intact temperate grasslands region remaining but are surrounded by some of the least intact grassland ecoregions (Scholtz & Twidwell 2022). What is left of the North American tallgrass prairie is estimated to be between 1% and 13% of the pre-European extent (Samson et al. 2004). Grassland biodiversity is also threatened, seen in the North American grassland avian communities where there has been a greater than 60% loss since the 1970's (Rosenberg et al. 2019). The Sandhills Task Force, a non-profit organization that aims to enhance Sandhills grasslands ecosystem, has identified six threats or stressors for the Nebraska Sandhills: changes in land use, disruption of disturbance regimes, energy development, invasive species, water quality and quantity, and wetland loss (Buell et al. 2013).

A Collaborative Adaptive Management (CAM) Project was started at the University of Nebraska in 2020 to address some of key uncertainties related to the management of grasslands in the Nebraska Sandhills through stakeholder driven experiments and the adaptive management cycle. CAM stakeholders are comprised of local ranchers, University of Nebraska researchers, Sandhills Task Force, Natural Resource Conservation Service, US Fish and Wildlife Service, and The Nature Conservancy (Martens 2023). Adaptive management is a learning through doing based approach that uses an iterative structured decision-making process to increase our understanding of a system (Holling & Walters 1978). It emphasizes the need to act, even though our knowledge is incomplete and despite uncertainties (Walters 1986). Adaptive management is different from trial-and-error methods because of the presence of the explicit decision-making structure that includes the defining of the problem and identification of the objectives, the evaluation and estimation of outcomes and tradeoffs, and the establishment of procedures for the collection of data followed by assessment and reiteration (Allen et al. 2011).

CAM has identified the following three areas of focus to address: reduction in woody and invasive species encroachment, increasing heterogeneity across landscape and species diversity, and evaluating economic and ecological trade-offs. To address these areas of focus CAM has implemented a modified patch-burn grazing system at the University of Nebraska-Lincoln's Barta Brothers Ranch (Martens 2023). Patch-burn grazing is a system that utilizes prescribed fire to burn different portions of a field each year while allowing cattle to have access to both the burned and unburned areas of the field. Cattle show a significant preference and utilization of recently burned areas leaving other sections to recover. As different sections are burned it shifts the cattle's grazing focus and creates a shifting mosaic of vegetation structure (Weir et al. 2013). The patch-burn grazing system has been modified by burning the entirety of one field in a four-field crossed fenced pasture system. Following the fire, all gates between fields were left open to allow the cattle to move freely and follow their preference in grazing area. The patch-burn grazing system has been modified to be used without the removal of any preexisting fencing and be more likely to be implemented within current management practices of the Nebraska Sandhills. Research has shown many benefits of this system such as controlling woody plant encroachment, mitigating drought impacts, increasing habitat heterogeneity, and increasing forage quality for livestock (Baker et al. 2023, Fuhlendorf et al. 2017, Fuhlendorf et al. 2009, Fuhlendorf et al. 2004, Weir et al. 2013). Many of the positive results around patch-burn grazing come from tallgrass prairie systems. In shortgrass prairie systems, patch-burn grazing did not have as large of an effect (Augustine & Derner 2015). The Nebraska Sandhills has a unique mix of tall and short grass vegetation which has an understudied response to a fire-grazing interaction.

At the Barta Brothers Ranch, an existing four field management unit was managed as a rotational grazing system with cross fencing separating fields. In 2022 a patch-burn grazing system, modified to operate without removing any fence, was implemented with a prescribed burn in March 2022. In this system one of the four existing fields is burned in its entirety and the existing gates between the pastures are left open, allowing cattle to preferentially select grazing areas. Each year a new field will be burned in rotation. To inform the adaptive management process, CAM has focused on monitoring the effects this system has on the spread of eastern red cedar, grassland vegetation communities and structure, grassland bird communities, soil health, and livestock performance (Martens 2023). In the chapters that follow, I assess the potential impacts that prescribed burning may have on soil health in the Nebraska Sandhills, determine effects of our modified patch-burn grazing system on vegetation communities and structural heterogeneity, and how the grassland avian community reacts to this new disturbance cycle and possible changes in their habitat structure.

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Chapter 2 – Short-term Impacts of Patch-burn Grazing on Nebraska Sandhills Soil Properties

Introduction

The dunes of the Nebraska Sandhills are thought to have been formed over the last five to ten thousand years during periodic extensive episodes of eolian activity (Swinehart 1998). While they are stabilized today, extensive reactivation of the dune fields has appeared at least three times in the past 4000 years (Schmeisser et al. 2015). The thin topsoil layer of the Sandhills is characterized by low water holding capacity, low natural fertility, and low organic matter content and is considered to be at a high risk of wind erosion if exposed (Stubbendieck et al. 1989, Lewis 1989). Blowouts, small-scale destabilizations typically caused by a lack of vegetation on exposed upper dune slopes and accumulated wind erosion, form depressions across the landscape and act as a reminder for potential large-scale destabilizations. The fear of destabilization and a desire for better rangeland conditions led to tight control of wildfires and changes in land management practices in the early 1900's (Stubbendieck et al. 1989, Holechek et al. 1989). Livestock producers in the Sandhills shifted management to discourage highly disturbed areas by using uniform moderate grazing and rest periods (Holechek et al. 1989). These management actions have succeeded in changing a landscape that once contained large blowout complexes to grassland interrupted by only relatively small and isolated pockets of blowouts (Fritz 1989).

The Great Plains region of North America has a long history associated with fire. Pre-European arrival, fire in many prairies had a return interval of 2-3 or 3-5 years which increased post European settlement to a mean return interval of up to 24 years (Cutter & Guyette 1994, Bragg 1986). This anti-fire sentiment that started with European settlers, prevailed through

1900's management and is still present in today's producers. Many producers in the Sandhills still view fire as unsafe, and either not providing any benefits that other management tools could achieve, or as an actively harmful event that inhibits their capability to produce and degrades the land (Sliwinski et al. 2018). Because of this sentiment, fire is not often used as a tool in this region, reducing the ability to control invasive woody species like eastern red cedar (Juniperus virginiana) and reducing the potential for rangeland vegetation heterogeneity (Fuhlendorf et al. 2017). At the University of Nebraska-Lincoln's Barta Brothers Ranch in the Nebraska Sandhill's the Collaborative Adaptive Management Project has implemented prescribed fire through a patch-burn grazing system in an effort to reduce woody encroachment, increase heterogeneity and biodiversity in the system and to evaluate the economic and ecological trade-offs produced from the patch-burn grazing (Martens et al. 2023). The potential trade-offs of this management is includes an increase in erosion and the degradation of soil nutrient conditions in burned units.

While many producers show concerns over the use of fire, the Sandhills have been shown to exhibit strong ecological resilience in the face of fire. Multiple studies have shown that the Sandhills are able to recover after wildfire and do not show any evidence for large-scale destabilization following wildfire events (Volesky & Connot 2000, Pfeiffer & Steuter 1994). Ecological resilience is the threshold level of disturbance that an ecosystem can withstand without changing the self-organized processes and structures that define its stable state. When this threshold is passed, the system transitions into a new state with its own self-organizing process that makes it difficult to transition back to the original (Holling 1973, Lewotin 1969, May 1977). Extreme circumstances such as wildfire compounded by drought were not able to push the Sandhills into another state and the above ground biomass in burned areas was able to recover in two years (Arterburn et al. 2018). While the Sandhills have been shown to be able to recover from fire in short time periods, no studies have been done to determine how these sandy soils move while the aboveground vegetation cover is still recovering.

Fire has been shown to have varied effects on soil conditions and nutrients based on a number of factors such as fuel load, fire intensity and severity, vegetation composition, and soil water saturation. Grassland fires tend to burn surface fuels quickly and move rapidly over the landscape, limiting the heat transferred to the soil and reducing the potential impact (Neary & Leonard 2020). One of the most commonly reported effects of fire is an increase in soil pH due to the denaturing of soil organic acids, the formation of oxides and the incorporation of ash into the soil (Pereira et al. 2014, Marcos et al. 2014, Certini 2005, Giovannini et al. 1988). Low severity fires and prescribed fires tend to show no to little increases in pH while moderate or severe wildfires typically significantly increase soil pH for a short to medium time after a fire, depending on the type of soil affected (Marcos et al. 2009, Úbeda et al. 2005, Murphy et al. 2006). This change in soil pH following fires can affect nutrient availability (Certini 2005). The effect that fire can have on soil organic matter (SOM) is highly variable and depends on the amount of direct access to the SOM and its interactions with decomposers and other minerals present. Fire can act to help stabilize SOM or it can deplete SOM (Pellegrini et al. 2022). For example, in a semiarid environment, experimental results showed that post prescribed fire, SOM significantly varied by vegetation type, but no difference was found before and after the fire (Pellegrini et al. 2022). The mineralization of organic matter following a fire and the incorporation of ash into burned soils can increase cation exchange capacity (CEC). This is due to an increase in the solubility of major cations such as magnesium (Mg), potassium (K), sodium (Na), and calcium (Ca) caused by the increase in pH. In contrast, minor nutrients such as sulfur (S), zinc (Zn), Iron (Fe), and manganese (Mn) may see a decrease in solubility (Ponder et al.

2009, Inbar et al. 2014, Badía et al. 2014). Nitrogen (N) and phosphorus (P) are often the dominant limiting nutrients in most natural systems. Nitrate, the form of N that is most often used by plants for growth and development, has shown short and long term increases in the soil following fires due to increases in temperature, pH and soil moisture, promoting an increase in nitrogen mineralization and the nitrification processes (Guignard et al. 2017, Rodríguez et al. 2009, Caon et al. 2014). Soils often contain a high content of phosphorus, but it is considered a limiting nutrient because it is mainly present in forms that are not available for plants. Available P content has been found to decrease after a fire due to the burning off of the litter layer and the removal of ash from the soil's surface through erosion processes, but fire has also shown to increase available P over time due to the persistence of ash deposition on the soil's surface (Ekinci et al. 2005, Caon et al. 2014).

The goal of this study is to determine if, over a short time period, the application of prescribed fire in a patch-burn grazing system increases detectable soil movement across the dunes of the Sandhills and if the treatment has an impact on soil properties such as organic matter content, pH, and soil nutrient levels. Based on current expectations, the treatment should allow for an increase in soil movement due to the removal of above ground biomass and exposure of the soil surface to the wind but not allow for enough movement that blowouts could form before vegetation recovers. There is concern that fuel build-up in a field that had not been historically burned could allow for a more intense fire that would have a negative impact on SOM content in the vulnerable topsoil of the Nebraska Sandhills. It is expected that a prescribed burn could decrease SOM in this system. Soil pH levels are expected to increase following a fire along with the nitrates, CEC and the major cation nutrients. Phosphorus as well as the minor nutrients are expected to decrease slightly following the fire. To address these expectations, soil conditions were monitored using soil samples taken before and for a period following the fire as well as monitoring the amount of soil movement at the surface of the soil using erosion pins.

Methods

This study took place at the University of Nebraska-Lincoln Barta Brothers Ranch in the Eastern Nebraska Sandhills (lat 42°13’32”N, long 99°38’09”W: elevation=765) containing approximately 2,400 hectares of rangeland. The property contains a mix of plant species typically found in the Sandhills region characterized by a mixed-grass prairie. The landscape consists of a mix of sub-irrigated meadows and wetlands making up 10% of the study area with the remaining 90% of the area classified as upland range (Schacht et al. 2000). The study site received an average of 505 mm of precipitation yearly from 2020-2023 with a mean annual temperature for this period of 11°C (HPRCC 2023). Soils at the site are characteristic of Sandhills soils, classified as Valentine fine sands (mixed, mesic Typic Ustipsamments) featuring a low water holding capacity and a high risk of wind erosion (USDA-NRCS 2007).

The Barta Brothers Ranch contains six management units that have historically been grazed in a traditional rotational grazing system (Figure 1). In this study, the treatment unit of focus is fields N5-N8 where patch-burn grazing was implemented. A prescribed burn was conducted in field N5 March 2022 and in field N6 in May 2023. Cattle were let into the management unit in late May of both years and had access to all four fields throughout the entirety of the grazing season.

To measure the effects of the treatment on the movement of the soil inside of the fields, erosion pins were installed. Pins were installed in April 2022 in field N5 after the prescribed fire and in field N8 at the same time to be used as a control. In May 2023, pins were installed in field

N6 after the 2023 prescribed fire. Between 30-38 pins were installed in each field, depending on obstacles within the fields, in a grid pattern (Figure 2). These pins were metal rods measuring ~90cm each and were installed to a depth of ~50cm, leaving ~40cm above ground. The installation at this height and a bright colored tape wrapping ensured the pins were easily visible above the vegetation. When the pins were installed, an initial measurement was taken to be used as the basis for any soil movement, and the vegetation coverage was noted as either light, medium or heavy. Topographic position (DT, NS, SS, and Interdunal) and percent slope were also recorded for each pin. Pins were routinely remeasured over the next year and a half. The difference between the repeated measurement and the original measurement represents the movement of the soil at that site. It was evident that cattle took interest in the pins by fur left over from rubbing on them, but the pins were not torn out of the ground or unduly impacted by the cattle.

To measure the effects of the treatment on soil properties, soil samples were taken before and after the prescribed fire and every month for the following four months during the grazing season. During the second year of this study, the prescribed fire burned with very low intensity and a complete burn was not accomplished, therefore it was decided to only collect before and after soil samples for monitoring purposes, which will not be reported on in this study. Soil samples were taken from four dunes across each field. At each dune samples were collected from sites on the dune top, north slope, and south slope (DT, NS, SS) resulting in 12 samples being taken in each field during each sampling period. At each sampling site six soil cores were taken at a 10cm depth and aggregate into a single sample. Samples were sent to Ward Labs, 4007 Cherry Ave, Kearney, NE 68847, for processing and testing. SOM was measured through the loss on ignition method where the percentage of mass lost from the soil sample after burning is the amount of SOM present in the sample. Nitrate was extracted from the soil with water saturated with a calcium solution. Plant available phosphorous was extracted using the Mehlich P-3 test. Calcium, Magnesium, and Potassium were extracted using a 1 N ammonium acetate solution. Sulfur was extracted using a 500 ppm calcium phosphate extractant. Zinc, Iron, Manganese and Copper were extracted with the chelating solution, DTPA.

To better represent the mobility of the soil in the Nebraska Sandhills resulting from the patch-burn grazing treatment, the absolute value (ABS) of the change in pin height will be used during in the analysis as this has been shown to be a better indicator than net real number change (Kearney et al. 2018). The change in soil height was analyzed using a linear regression and a repeated measures ANOVA. A test for sphericity was used alongside of the ANOVA to ensure that the data was meeting the assumption of the analysis. The linear regression evaluated the ABS movement of soil using the final measurement taken at each pin. The final model set used to assess the ABS movement of soil included sixteen models evaluating the effect of the following variable of interest; Topographic Position, Percent Slope, Cover, and Field (burned/unburned). Akaike information criterion (AIC) was used to select the potential model that best fits. The repeated measure ANOVA was used evaluate the movement of soil through time for pins located in each field. In case of significant differences, pairwise comparison was used to identify those differences. The data resulting from soil testing did not follow assumptions of a normal distribution or homogeneity of variances, even after square root and logarithmic transformations. Due to this, comparison between the burned and unburned samples were carried out using the non-parametric Mann-Whitney U (MU) test along with the calculation of Hodges-Lehmann estimates, the median possible difference between two groups when taking one observation from each sample. The Kruskal-Wallis test (K-W) was used to identify significant differences between sampling dates for each response variable. If significant differences were observed at $p < 0.05$, the multiple comparisons rank test was carried out to identify differences. All analyses were performed using the packages *lme4* and *stats* in the R statistical computing software (R Core Team 2022).

Results

The mean ABS moment of soil for pins were N5= 0.903 cm (burned), N6=0.86 cm (burned), and N8=0.631 cm (unburned). The top ranked model, according to AIC selection in the set evaluating ABS soil movement, was the null model (*w*=0.293; Table 1). The repeated measures analysis within fields N5 and N6 found no significance between measurements over time in the movement of soil. The repeated measures ANOVA for field N8 failed in the test for sphericity and so a sphericity correction was used to calculate a p-value of 0.008, indicating a significant difference. The following pairwise comparison found that the measures taken in May 2022 were significantly different than measurements taken in 2023 and that June 2023 was significantly different from measurements taken in June and July of 2022 (Table 2). The ABS soil movement in field N8 was significantly less in May of 2022 than in 2023 and that it was higher in June of 2023 than in June and July of 2022 (Figure 3).

There were no significant differences in the pH levels between burned and unburned fields, but both saw a significant increase in April, one month following the prescribed burn. Cation exchange capacity (CEC) saw a slightly significant drop during this same period, but later regained similar levels over the following months (Table 3). Both burned and unburned samples saw a similar significant decrease in nitrate concentration throughout the growing season but were significantly different in July where unburned moved back to levels seen in the beginning of the study while the unburned stay significantly lower. Potassium was significantly lower in the burned fields before and immediately after the fire but during the rest of season there was no difference. There was a significant decrease of salt in July for both burned and unburned (Table 4). Sulfur saw a significant increase in the burned field during April but no difference between burned and unburned. Manganese saw a significant increase immediately following the fire in the burn field and stayed at that level of concentration for the remainder of the growing season. The unburned field saw a similar pattern of increase that started in April (Table 5).

Discussion

The aim of this study is to evaluate the potential impacts a newly introduced patch-burn grazing system has on the health of the soil in the Nebraska Sandhills. The use of fire as a management tool is poorly understood in this ecoregion but patch-burn grazing systems have been shown to have many beneficial effects such as increases in vegetation heterogeneity, biodiversity, and cattle production and a decrease in woody species encroachment (Fuhlendorf et al. 2017, Fuhlendorf et al. 2009, Fuhlendorf et al. 2004, Weir et al. 2013). Fire can have both positive and negative impacts on soil health depending on the intensity of the fire and the soil substrate with which the fire is interacting (Neary & Leonard 2020, Pellegrini et al. 2022, Badía et al. 2014). If this system is to be used as a management technique in the Sandhills the possibility of negatively impacting soil health needs to be understood.

During this study, no support was found for an increase in soil movement between burned and unburned fields as measured by the changes of soil height at erosion pins. The movement of soil appeared to be higher in N5 throughout the study (Figure 3) but the best fitting model was the null mode, supporting the null hypothesis of no difference due to any of the predictor variables used, including burned and unburned fields. The analysis of the repeated measures shows that there were not any major changes in the soil movement in each of the fields through the time of the study.

The reaction of pH to the prescribed fire was within expectations and is supported by the literature in that a slight increase was seen following the fire (Marcos et al. 2009, Úbeda et al. 2005, Murphy et al. 2006). The similar increase in pH seen in the unburned field could be caused by ash deposition as prevailing winds on the day of the prescribed burn pushed smoke over the unburned field. This study found no significant impacts to the percent content of SOM. The fast-burning nature of a grassland fire coupled with a less intense controlled burn led to no noticeable decrease in SOM. The only significant difference in CEC was between immediately after the burn and one month after in April where it dropped from 4.85 meg/100g to 4 meg/100g. While this was statistically significant, it is not necessarily biologically significant. CEC values under 10 meg/100g are generally considered low for agricultural production and CEC between 3-5 meg/100g are considered normal for light-colored sandy soils such as those found in the Sandhills (Mengel 1993).

Of the major nutrients analyzed in this study (Table 4) only nitrate, potassium, and sodium had any significant differences. Nitrate concentration in both fields decreased throughout the growing season but differed in July where the unburned levels increased back to their original levels. The decreases in nitrate were most likely caused by plant uptake outpacing the nitrification process through the growing season. Some studies have found that soil nitrogen content can be decreased by more intense grazing due to inhibiting plant biomass accumulation and microbial activity as well as reduced nitrogen input (Chen et al. 2023, Zhou et al. 2017). A more intense grazing pressure in the burned field caused by the cattle's preferential grazing could account for the lower nitrate levels in the burned field during July. These results do not meet the expectations that there would be an increase in soil nitrate concentrations in the burned field. This may be attributed to a lower than optimal pH levels (7-8) for microbial nitrification. While there was an increase in pH, it did not rise to be in that optimal range and therefore would have less of an effect on nitrate levels. Potassium was significantly lower than in the burned field before and right after the fire but increased in the following months to be similar to the concentrations found in the unburned, though this was not found to be a significant change within the burned field through time. Sodium showed an increase immediately after the prescribed fire in the burned field then both fields showed a decrease through the growing season in a similar to the pattern to the nitrate concentrations. Of the minor nutrients (Table 5) both sulfur and manganese saw minor increases following the fire, but the burned field did not differ from the unburned field.

This study supports the idea that following the implementation of a patch-burn grazing system in the Nebraska Sandhills, there is no degradation of soil health resulting from treatment. While the image of abundant bare soil following a burn brings to mind massive potential for erosion, the fire was not enough of a disturbance any significant movement of the soil. This is supported by the findings of Hartman (2015), that only after five years of vegetation suppression did the complex system of roots stabilizing the sand dunes break down and allow for rapid erosion. Any visual of moving sand seen following the burn was local movement that in the end did not displace any significant amount of soil. The lower intensity of a prescribed burn and the fast-burning nature of grassland fires resulted in little impact of the composition and nutrients of the soil. The theory that the fire could negatively affect soil organic matter was not upheld as the percentage contained in samples held steady throughout the study. The lower intensity of the prescribed fire did not create conditions that would allow for a significant affect to the nutrient profile of the burned field. The results of this study indicate that fire and patch-burn grazing can be used as a management tool in the Nebraska Sandhills without damaging the soil health. This study was only conducted over a relatively short term compared to the planned four-year rotation of a patch-burn grazing system. Further study needs to be done to determine how one or more rotations of this system might affect soil where it is implemented. This study was also only conducted inside one set of fields under the patch-burn grazing system. As the use of fire as a management tool becomes more accepted for the Nebraska Sandhills and the use of it spreads, further study should be done to support these findings.

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Tables

Table 1. Model selection table for the relationship between soil movement and the possible covariates % Slope Angle, Topographic Position, Cover, and Field. Values reported include number of parameters (K), Akaike's Information Criterion corrected for small sample sizes (AICc), difference in AICc from the best fitting model (ΔAIC), model weight (w), and the log-likelihood (LL).

Models	K	AICc	Δ AIC	*w*	LL
Null	2	295.1591	0	0.293	-145.518
Slope	3	296.3241	1.164996	0.164	-145.038
Topo	6	296.7724	1.613317	0.131	-141.939
Slope+Cover	5	297.4605	2.301363	0.093	-143.415
Cover	4	297.574	2.414838	0.088	-144.579
Slope+Topo	7	297.9619	2.802791	0.072	-141.379
Field	4	299.3153	4.15622	0.037	-145.449
Cover+Topo	8	299.6285	4.469429	0.031	-141.032
Slope+Cover+Topo	9	299.8796	4.72052	0.028	-139.951
Slope+Field	5	300.631	5.471922	0.019	-145
Field+Topo	8	301.2718	6.112635	0.014	-141.853
Field+Cover	6	301.8549	6.695733	0.010	-144.481
Slope+Field+Cover	7	301.9966	6.837449	0.010	-143.396
Slope+Field+Topo	9	302.6341	7.474973	0.007	-141.328
Field+Cover+Topo	10	304.3195	9.16043	0.003	-140.938
Slope+Field+Cover+Topo	11	304.7557	9.596575	0.002	-139.895

Table 2. Results of ABS soil movement pairwise comparison for field N8 following a repeated measures ANOVA found there to be a significant difference over time. Significance indicated by

	Apr-23	Jul-22	Jul-23	Jun-22	Jun-23	May-22	May-23	Sep-22
Jul-22	0.088	-	-	-	-	-	-	-
Jul-23	0.921	0.07	-	-	-	-	-	-
Jun-22	0.239	0.673	0.226	-	-	-	-	-
Jun-23	0.492	**0.014**	0.525	**0.04**	-	-	-	-
May-22	**0.018**	0.571	**0.015**	0.277	**0.002**	-	-	-
May-23	0.911	**0.06**	0.921	0.196	0.571	**0.014**	-	-
Sep-22	0.921	0.111	0.898	0.277	0.402	**0.022**	0.839	-
Sep-23	0.726	0.238	0.673	0.501	0.239	0.059	0.622	0.821

Table 3. Median values of Soil pH, Organic Matter loss on ignition (OM LOI%), CEC, and Nitrate (ppm) and Phosphorus (ppm) concentrations in the burned (N5) and unburned (N8) fields during the study period. Kruskal-Wallis (K-W), comparing burned and unburned, and Mann-Whitney (MU), comparison over time, p-values (*p < 0.05, **p < 0.01, ***p < 0.001, and ns – non-significant at p < 0.05) are shown for each comparison. Hodges-Lehman estimate reported to more accurately interpret median differences between samples for each MU comparison.

		Before fire	After fire	April	May	June	July	K-W
pH	Burned	5.9	5.8	6.25	6.15	5.9	6.05	***
	Unburned	5.9	5.9	6.3	5.95	6	6.2	***
	Hodges-Lehmann Estimate	0.00005	0.08011	0.00003	0.19997	0.09999	0.09999	
	Wilcoxon	ns	ns	ns	ns	ns	ns	
OM LOI%	Burned	1.2	1.2	1.35	1.3	1.15	1.2	ns
	Unburned	1.25	1.2	1.3	1.2	1.2	1	ns
	Hodges-Lehmann Estimate	0.00002	0.09997	0.00004	0.00003	0.09993	0.20005	
	Wilcoxon	ns	ns	ns	ns	ns	ns	
CEC per 100g	Burned	4.6	4.85	4	4.45	4.45	4.25	*
	Unburned	5.05	4.75	4.25	4.6	4.5	4.2	ns
	Hodges-Lehmann Estimate	0.19991	0.19997	0.19997	0.19993	0.10003	0.2	
	Wilcoxon	ns	ns	ns	ns	ns	ns	

Table 4. Median values of major nutrient concentrations in the burned (N5) and unburned (N8) fields during the study period. Kruskal-Wallis (K-W), comparing burned and unburned, and Mann-Whitney (MU), comparison over time, p-values (*p < 0.05, **p < 0.01, ***p < 0.001, and ns – non-significant at p < 0.05) are shown for each comparison. Hodges-Lehman estimate reported to more accurately interpret median differences between samples for each MU comparison.

		Before fire	After fire	April	May	June	July	K-W
K ppm	Burned	83.5	85	96.5	96.5	82	88	ns
	Unburned	92.5	96	97	88	89	89	ns
	Hodges-Lehmann Estimate	7.99995	9.99997	3.00001	8.23124	1.00003	1.00005	
	Wilcoxon	*	*	ns	ns	ns	ns	
Mg ppm	Burned	57.5	59	61	66.5	60	61	ns
	Unburned	57	60	67.5	63	62.5	62	ns
	Hodges-Lehmann Estimate	1.49869	3.00007	5.00002	0.99999	1.80861	4.46616	
	Wilcoxon	ns	ns	ns	ns	ns	ns	
Na ppm	Burned	6.5	8	7	6	5.5	5	***
	Unburned	7	7	7	6	6	5	***
	Hodges-Lehmann Estimate	0.99994	0.00003	0.00001	0.00005	0.00004	0.99997	
	Wilcoxon	ns	ns	ns	ns	ns	ns	
Ca ppm	Burned	359.5	364	371	387.5	391	386	ns
	Unburned	376	365	401	413	384.5	398	ns
	Hodges-Lehmann Estimate	17.8693	4.21828	20.9999	22.7739	2.00002	9.00004	
	Wilcoxon	ns	ns	ns	ns	ns	ns	
Nitrate ppm	Burned	1.05	1	0.5	0.2	0.05	0.35	***
	Unburned	1.1	1.25	0.6	0.05	0.125	0.9	***
	Hodges-Lehmann Estimate	0.27402	0.29999	0.09997	0.00004	0.00003	0.34991	
	Wilcoxon	ns	ns	ns	ns	ns	*	
P ppm	Burned	13	12.5	15	12.5	12.5	13	ns
	Unburned	13	13	14	16.5	15	14	ns
	Hodges-Lehmann Estimate	2.00005	1.00005	0.00007	3.23077	2.00005	0.00004	
	Wilcoxon	ns	ns	ns	ns	ns	ns	

Table 5. Median values of minor nutrient concentrations in the burned (N5) and unburned (N8) fields during the study period. Kruskal-Wallis (K-W), comparing burned and unburned, and Mann-Whitney (MU), comparison over time, p-values (*p < 0.05, **p < 0.01, ***p < 0.001, and ns – non-significant at p < 0.05) are shown for each comparison. Hodges-Lehman estimate reported to more accurately interpret median differences between samples for each MU comparison.

		Before fire	After fire	April	May	June	July	K-W
S ppm	Burned	4.7	5.65	6.75	4.6	5.45	5.8	***
	Unburned	5.1	5.45	5.8	6.4	5.75	5.5	ns
	Hodges-Lehmann Estimate	0.10002	0.25382	0.60002	1.39995	0.63393	0.70001	
	MU p	ns	ns	ns	ns	ns	ns	
Zn ppm	Burned	0.61	0.72	0.895	0.855	0.85	0.585	ns
	Unburned	0.755	0.625	0.97	0.955	0.825	0.675	ns
	Hodges-Lehmann Estimate	0.17497	0.11435	0.07008	0.09517	0.02004	0.04007	
	MU p	ns	ns	ns	ns	ns	ns	
Fe ppm	Burned	18.8	19.65	17.75	17.55	17.9	17.55	ns
	Unburned	20.75	19.95	17.8	18.75	17.8	16.45	ns
	Hodges-Lehmann Estimate	1.23546	0.24659	0.07589	0.08499	0.45371	1.1224	
	MU p	ns	ns	ns	ns	ns	ns	
Mn ppm	Burned	2.4	4	5.15	4.35	4.7	3.55	***
	Unburned	3.5	2.7	5.1	5.2	4.95	4.2	**
	Hodges-Lehmann Estimate	0.99996	1.20003	0.29994	0.10002	0.15245	0.4	
	MU p	ns	ns	ns	ns	ns	ns	

Figures

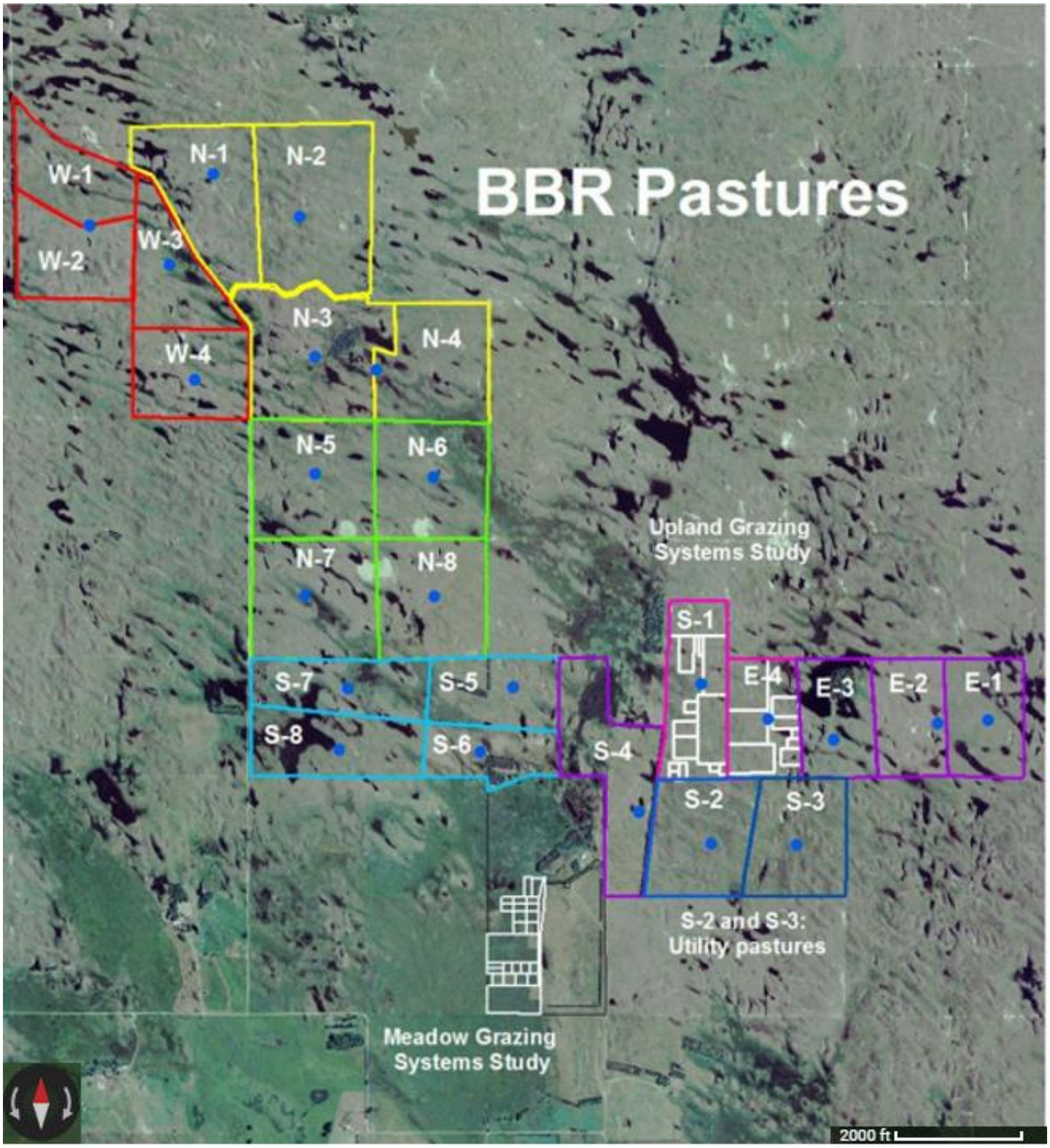


Figure 1. Map of the Barta Brothers Ranch highlighting the different pastures and management units. https://extension.unl.edu/statewide/enre/bbr-pastures-edwards-unit.jpg

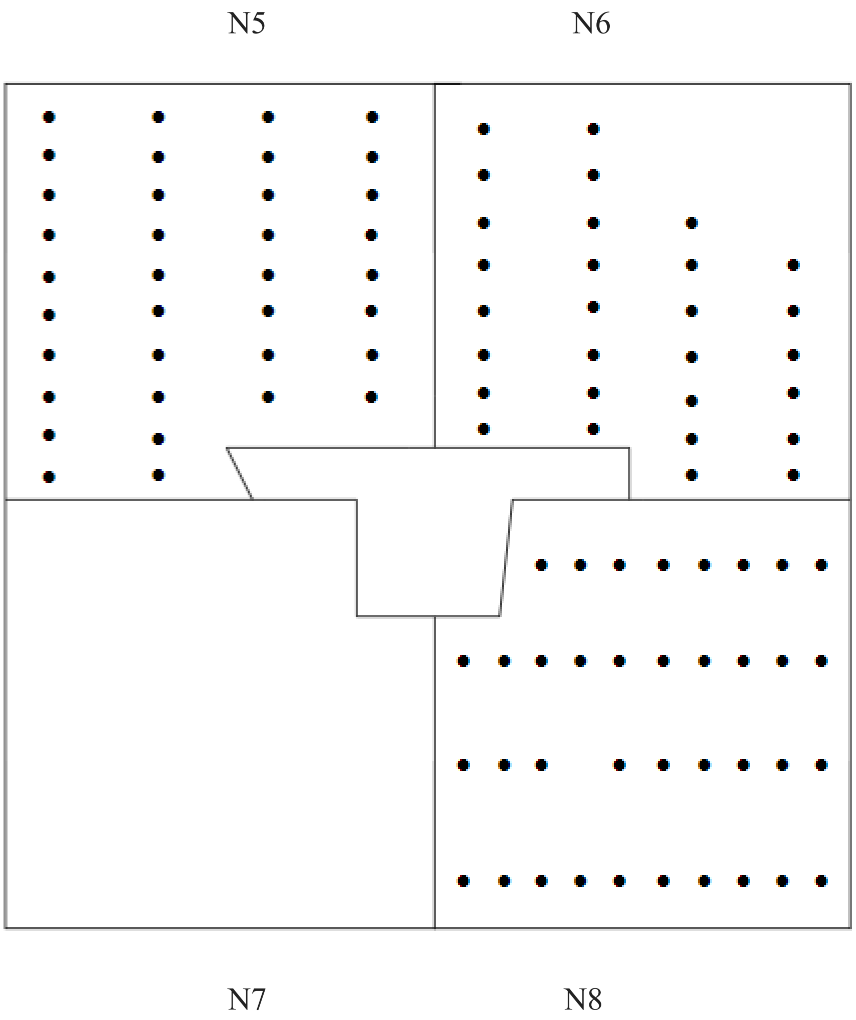


Figure 2. Placement of erosion pins throughout treatment fields. Pins were installed in N5 and N8 in April 2022 following the March 2022 prescribed fire in N5. Pins were installed in N6 following the May 2023 prescribed burn.

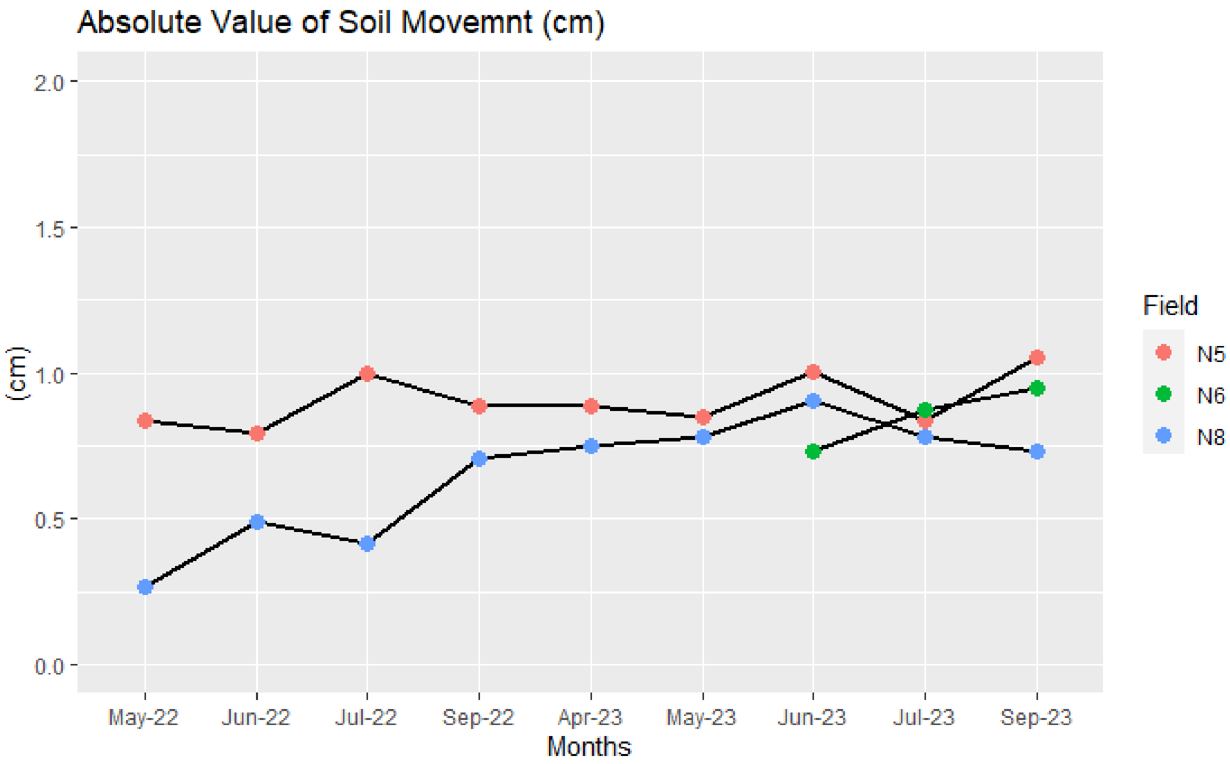


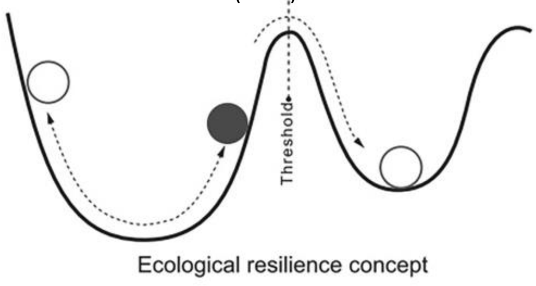
Figure 3. Line graph plotting the average ABS movement of soil of pins located in each field in each month that measurements were taken. Burns were conducted in late March 2022 and May 2023 in field N5 and N6 respectively. This data reflects the change in height of soil after the first measurements were taken.

Chapter 3: Increasing Vegetation Heterogeneity in the Nebraska Sandhills through Patch-Burn Grazing

Introduction

Grasslands have long been managed to reduce variability and increase predictability in forage production through management such as uniform moderate grazing and deferment or rest periods that encourages homogeneity (Fuhlendorf et al 2017, Holechek et al 2011). A recent focus on how complex ecological systems develop and sustain themselves has led to an understanding of the importance of variability in nature and how heterogeneity and biodiversity lead to an increase in stability and resilience (Fuhlendorf et al 2017). Ecological resilience is the amount of disturbance that an ecosystem can withstand without changing the self-organized processes and structures that define its stable state. When this threshold is passed, the system transitions into a new state with its own self-organizing processes which are often difficult to transition back to the original (Holling 1973, Lewontin 1969, May 1977). The ball-and-cup model (Figure 1) is a widely recognized heuristic model of ecological resilience in which the ball, representing an ecosystem, remains within a set of bound conditions, representing the stable state, until such a time where perturbations are enough to move the ball across a threshold and into a new stable state (Holling 1973). As a heuristic, the model works well, but its applied use may be limited. For example, while the ball-and-cup model displays an ecosystem's heterogeneity, the depth and width of the cup, the

Figure 1. The theoretical ball-and-cup diagram used to depict ecological resilience as introduced by Holling (1973)



temporal variability or the ability for that shape to change over time as the heterogeneity and resilience increases or decreases, is not shown (Desjardins et al 2015).

Heterogeneity in grasslands typically originates from two sources, inherent heterogeneity and disturbance driven heterogeneity. Inherent heterogeneity is driven by the variation of abiotic features on the landscape and disturbance-driven heterogeneity is variability derived from processes or perturbations (Fuhlendorf et al 2017). In grasslands, the inherent heterogeneity in community composition, production, and diversity can vary widely across scales driven by geological and topoedaphic variations such as soil type, variability in topography, and hydrological conditions (Fuhlendorf & Smeins 1998, Fuhlendorf et al. 2009, Duquette et al. 2022). Disturbances, such as fire, interact across the landscape with differential timing and correspond with successional stages among patches that create heterogenous conditions known as a shifting mosaic (Fuhlendorf & Engle 2004). Disturbance-driven heterogeneity in grasslands has long been minimized in favor of promoting uniform grazing distribution and "managing for the middle" (Twidwell et al. 2013, Fuhlendorf et al. 2012).

The Nebraska Sandhills, part of the larger Great Plains region of North America, are one of the world's most intact temperate grasslands regions. They are characterized by a semi-arid mixed grass prairie with rolling grass-stabilized sand dunes and are surrounded by some of the least intact grassland ecoregions (Scholtz & Twidwell 2022). What is left of the North American tallgrass prairie is estimated to be between 1%-13% of the original pre-European extent (Samson et al. 2004). There is a call to shift the focus of grassland conservation to the proactive and preventative management of threats to large-scale tracts of intact ecosystems comprised mostly of native plant communities within otherwise less intact landscapes. This creates the challenge of finding management strategies that can be implemented at a large enough scale to effect change

(Maestas et al. 2022). Increasing disturbance-driven heterogeneity in the Sandhills by utilizing a combination of different grazing systems across the landscape found that grazing alone did not significantly increase heterogeneity and the study concluded that a fire grazing interaction would likely be needed (Sliwinski et al. 2019).

Patch-burn grazing has been introduced in other grassland systems as a way to implement a pyric-herbivory interaction in grasslands in an effort to increase resilience through heterogeneity and biodiversity while still maintaining commercial productivity (Fuhlendorf et al. 2009, Fuhlendorf & Engle 2004, Augustine & Derner 2015). Patch-burn grazing is a system that utilizes prescribed fire to burn different portions of a unit each year while allowing cattle to have access to both the burned and unburned areas of the unit. Cattle show a significant preference and utilization of recently burned areas leaving other sections to recover. As different sections are burned it shifts the cattle's grazing focus and creates a shifting mosaic of vegetation structure (Weir et al. 2013). The Nebraska Sandhills has a history of viewing fire negatively that conflicts with attempts to use fire in the region. Many producers still view fire as unsafe and unable to provide benefits that outweigh the risks (Sliwinski et al. 2018). Contrary to that opinion, studies have shown the Sandhills to be more resilient in the face of fire than previously thought, with multiple instances of the Sandhills recovering after wildfire and not showing any evidence for large-scale destabilization following wildfire events (Volesky & Connot 2000, Pfeiffer & Steuter 1994, Arterburn et al. 2018). One study in the Sandhills has tested a patch-burn grazing system but found no increase in the heterogeneity of vegetation structure due to the implementation of a patch-burn grazing system. This was attributed to the low stocking rate used in the study that limited grazing pressure and may have led to the rapid regrowth of vegetation. It was concluded that more research into the use of patch-burn grazing needed to be conducted in the Nebraska Sandhills (Arterburn et al. 2019).

At the University of Nebraska-Lincoln’s Barta Brothers Ranch in the Nebraska Sandhill’s a Collaborative Adaptive Management Project has implemented prescribed fire through a patch-burn grazing system with the goal of reducing woody encroachment, increasing heterogeneity and biodiversity in the system and evaluating the economic and ecological trade-offs produced from the patch-burn grazing (Martens 2023). The system has been modified for easier implementation with traditional Nebraska Sandhills ranching practices. Many ranchers use cross-fenced pasture systems and so the patch-burn grazing has been modified to eliminate the need to remove preexisting fencing. In the four-field treatment unit, the entirety of one field will be burned and the gates to the other fields in the system left open to ensure the cattle has access to the whole area. Prescribed fires were conducted in 2022 and 2023 as part of this project and will continue in the future. This study examines the changes in the vegetation structure and community of working grasslands in the Nebraska Sandhills following fires in 2022 and 2023 with the purpose of determining the ability of a patch-burn grazing system to shift the landscape into a more heterogeneous state. The expectation is that the interaction between fire and grazing will apply enough pressure to the system to impact the vegetation structure and increase heterogeneity of the Nebraska Sandhills grassland.

Methods

This study took place at the University of Nebraska-Lincoln Barta Brothers Ranch in the Eastern Nebraska Sandhills (lat 42°13’32”N, long 99°38’09”W: elevation=765) containing approximately 2,400 hectares of rangeland. The property contains a mix of plant species typically found in the Sandhills region characterized by a mixed-grass prairie. The landscape consists of a mix of sub-irrigated meadows and wetlands making up 10% of the study area with the remaining 90% of the area classified as upland range (Schacht et al. 2000). The study site received an average of 505 mm of precipitation yearly from 2020-2023 with a mean annual temperature for this period of 11°C (HPRCC 2023). Soils at the site are characteristic of Sandhills soils, classified as Valentine fine sands (mixed, mesic Typic Ustipsamments) featuring a low water holding capacity and a high risk of wind erosion (USDA-NRCS 2007).

The Barta Brothers Ranch contains 6 management units that have historically been grazed in a traditional rotational grazing system (Figure 2). In this study, the management unit of N5-N8 is the treatment unit for patch-burn grazing and will hereafter be referred to as the North unit. The management unit of W1-W4 acts as a control unit to compare the results of patch-burn grazing to traditional rotational grazing and will hereafter be referred to as the West unit. Both units were stocked with spayed heifer cattle at approximately 0.65 AUM ha^{-1} and ranged in size from 57 to 65 hectares (Martens 2023). Patch-burn grazing was implemented in this study by burning the entirety of a field in the North unit and allowing cattle to have access to the whole unit by way of open gates, including the recently burned field, to allow cattle to preferentially graze. Each year a new field will be burned in rotation, allowing three years of recovery before a field is burned again. The West unit will follow a traditional rational grazing system (Figure 3). Field N5 was burned in March of 2022 and field N6 was burned in May of 2023. The fire in N5 resulted in a much more complete burn than N6 due to the later timing of the burn and weather conditions of the day N6 was burned. By burning in March, higher quantity of green vegetation and a higher humidity caused the burn to be more inconsistent (Figure 4). Cattle were released into the N unit in late March both years. Cattle were released into the W unit at the same time and rotated fields every 1-2 months.

In each pasture 40 sampling points (32 in field W3 due to smaller size of the field) were established across the field and at different topographic positions to collect vegetation structural and community composition data. These points were loaded in GPS handheld units to be able to locate them in the field. Then, a 1m x 0.25m frame was placed on the ground to establish the sampling quadrat and large staples with brightly colored tape tabs were driven into the ground to at the corners of the quadrat to mark the location for future measurements. The following structural measurements were collected from these quadrats: visual obstruction reading (VOR) using the Robel Pole (using 2.5cm increment segments) (Robel et al. 1970), tallest plant height, litter depth averaged from three measurements in frame, bare ground cover estimate, litter cover estimate, standing dead cover estimate, plant functional groups (warm season grasses, cool season grasses, forbs, sedges, and woody shrubs) cover estimates, and topographic position on dunes (North Slope, South Slope, Dune Top and Interdunal swales). Additionally, all species inside of the frame were identified and cover estimated. All cover estimates were based on Daubenmire (1959) cover classes and the proportion of canopy covering the soil surface inside of the frame. Vegetation measurements were taken twice a year in June and August corresponding with peak cold season and warm season grasses growth periods.

Vegetation structural metrics and plant community were analyzed using nonmetric multidimensional scaling (NMDS), a distanced based ordination technique, to visually describe differences. The NMDS plots samples in space with the distance between samples corresponding to the similarity among samples (Arterburn et al. 2018, Debinski et al. 2011, Moranz et al. 2012). Vegetation structure and plant community were analyzed separately and species that occurred in less than 5% of samples were removed to focus on the relationships between dominant species (Arterburn et al. 2018, Laughlin & Fule 2008, McCune et al. 2002). Data was plotted separately for each sampling period so the change over time during treatment could be evaluated. Ellipses encompassing the normal distribution for the feature with the corresponding color and large centroids marking the mean position within those groups in the ordination were added to differentiate and described the different features being evaluated. Vegetation structure and plant community were evaluated at the management unit level (N-W) and at the field level (N5-N8, W1-W2) to better understand the effects of the treatment at different scales. The plant community was also evaluated using topographic position, as it has been shown to impact the composition and diversity of the community (Fuhlendorf & Smeins 1998, Fuhlendorf et al. 2009, Duquette et al. 2022).

A pairwise comparison using permutational multivariate analysis of variance (PERMNOVA) was used to test for significant differences in the burn fields' structural metrics from the unburned fields. (Anderson 2014, Sepp et al. 2021). A pairwise comparison using multivariate test for homogeneity of variance (Beta dispersion) was also used to analyze the impact on the heterogeneity of vegetation structural metrics, as measured by the variance in the distance of points in space from the group mean, as well as provided a check for Type II errors in the PERMNOVA by testing the assumption of equal variance (Raynor et al. 2021, Schloss 2008). The resulting p-values of the pairwise comparison were adjusted with the Benjamini–Hochberg method to control the false discovery rate. The Shannon Diversity index was calculated, using estimated cover in place of abundance, for all samples and a one-way analysis of variance (ANOVA) was used to compare fields in 2022 and 2023. All analyses were performed using the R statistical computing software (R Core Team 2022). The NMDS, PERMNOVA, and Beta dispersion were performed using Bray-Curtis distance and the respective functions in the vegan package: Shannon, metaMDS, Adonis, and betadisper (Oksanen et al. 2016).

Results

A total of 117 plant species were recorded throughout the course of the study (Table 1). Notable descriptive results include the average litter depth of N5 in 2022 = 0.33cm and 2023 = 0.48 cm. All other field averages ranged from 1.48-3.04 cm. N6 average liter depth also decreased from 2.89cm in 2022 to 1.59cm in 2023. N5 averaged a VOR of 2.96 in 2022 and increased to 5.36 in 2023 while all other fields averaged between 4.38-7.11. The average percentage of bare ground for N5 was 29.81% in 2022 and 34.5% in 2023 and N6's average percentage of bare ground increased from 6.16% in 2022 to 20.11% in 2023. All other fields averaged below 21.83%. Finally, the average percentage of forb cover for N5 in 2022 was 17.18% and dropped to 9.37% in 2023 with W3 in 2023 having the next highest average percentage of forb cover at 13.66%. (Table 2 & Figure 5).

NMDS ordination analysis of vegetation structural metrics shows that after two years, patch burn grazing did not cause a shift in the vegetation structure or heterogeneity at a management unit level (Figures 6 and 7). NMDS ordination analysis of vegetation structural metrics shows a shift in the structure at the field level. In June and August of 2022, field N5's ellipse representing the normal distribution of the group and the centroid marking the mean of the group, had shifted away from the other groupings (Figure 8). In June 2023 N5 was less distinct but still slightly apart. By August 2023 N5 was no longer noticeably separated (Figure 9). In June 2023 field N6 had moved in the direction of N5 but had not separated fully from the main cluster. By August 2023, N6 showed no discernable difference from other groups (Figure

9). NMDS analysis of vegetation communities showed no differences between groups at either the management unit level or the field level (Figures 10 and 11). In June 2022, NMDS did show separation of plant communities found in Interdunal areas, but this difference was not apparent at other times (Figure 12). The ANOVA of the calculated Shannon's Diversity Index (Table 3) reported a p-value of 0.000366 but the following post-hoc Tukey did not show any significant pairings.

Supporting the findings of the vegetation structural NMDS analysis, the pairwise comparison of PERMNOVAS analyzing the distance between the means of the fields, found N5 to be highly significantly different from all other fields in June and August of 2022 (Table 4). In June of 2023 N5 was still structure was still significantly different from all fields except N6 and in Augst 2023 N5 was no longer significantly different than fields N8 and W1 (Table 5). N6 was significantly different from the W fields in June 2023 but only W2 by August 2023 (Table 5). The pairwise comparison of Beta dispersion found few instances of significance in the variability of vegetation structural metrics. Of note though are the comparisons between N5 and W1 and W2 in August 2023, where N5 is significantly less variable and calls into question the differences found between their means in the PERMNOVA.

Discussion

Patch-burn grazing is being introduced to the Nebraska Sandhills as a way to increase the resilience of the ecosystem by increasing heterogeneity and biodiversity and decreasing invasive species while balancing ecological and economic tradeoffs in a working landscape (Martens 2023). While this system has been used in other grassland ecoregions to increase heterogeneity and biodiversity (Fuhlendorf et al. 2009, Fuhlendorf & Engle 2004). The use of prescribed fire in the Sandhills is relatively new and the effects of patch-burn grazing in the region are not well understood (Sliwinski et al. 2018, Arterburn et al. 2019). The data collected in this study suggests that patch-burn grazing has the ability to induce change in vegetation structure but did not significantly affect the plant community composition. The data did not show an increase in structural heterogeneity at the larger management unit level, but it did induce structural heterogeneity between fields, with the significant difference in vegetation structures seen in burned and unburned fields. One of the limiting factors in the previous attempt to increase heterogeneity in the Nebraska Sandhill was the inability to apply enough pressure to vegetation regrowth to create a sustained effect in the vegetation structure. This study showed a persisting change in the vegetation structure in the burned field through the second year that suggests there is potential, after more years of treatment, to create heterogeneity at a larger level.

The first year of this study saw a noticeable difference in vegetation structure of field N5. This is most likely due to the fire burning away the accumulated litter and standing dead material and resulted in a reduced vegetation density, as measured by VOR, and greater exposed bare ground. The residual difference found in June of the following year indicates that the grazing pressure exhibited throughout the first year was high enough to sustain the changes to the vegetation structure for a time. N6 saw a slight change in June 2023 after the second-year fire but the effect did not persist into August. The patch-burn grazing failed to increase the plant structural heterogeneity at either the field level or the management unit level and also failed to shift the plant community. There appeared to be an increase in forb cover following the prescribed fire, but the effect did not persist and was not apparent in the NMDS analysis. The ANOVA comparing Shannon Diversity Index presenting a significant p-value without any significant interaction during the pos-hoc indicates that there is some difference among the means but there is not enough information to draw conclusions on the source of that difference.

For patch-burn grazing to increase heterogeneity on the landscape Allred et al. (2011) and McGranahan et al (2012) hypothesized that fire must first be applied in discrete patches on the landscape, then the fire must be the primary driver of grazing selection and lastly that forage demand must correspond to forage supply at a moderate grazing pressure. Arterburn et al. (2019) attributed their inability to affect change in vegetation structure though patch burn grazing to a low stocking rate of bison (0.85 AUM ha^{-1}) and the rapid regrowth of vegetation. This study also used a low stocking rate (0.65 AUM ha^{-1}) but with cattle instead of bison and implemented fire across smaller patches. The application of fire across an entire landscape can remove the interaction between burned and unburned areas and creates a homogeneously burned landscape (Allred et al. 2011). The use of different large grazing herbivores and the application of fire in smaller discreet patches could explain the difference in findings. Fire's ability to attract grazers and influence vegetation dynamics is also lost when fire intensity is constrained by factors such as increased fuel moisture or unfavorable weather conditions (McGranahan et al 2014). The prescribed burning of N6 in March 2023 allowed for an increase in vegetation growth before the fire and an increase in fuel moister that limited the direct impact fire had and may have contributed to the loss in ability to attract grazers.

This study's ability to find evidence relating to changes at the management unit level was limited by the duration of the study and the lack of a complete burn in 2023. Patch-burn grazing produces heterogeneity across a landscape through disturbances that shift different successional states across that landscape in a shifting mosaic pattern of burn and recovery (Weir et al. 2013). This study covers the first two years of a four-year patch-burn grazing cycle on a landscape that has not been managed with fire in recent history, with the addition of a patchy incomplete fire the second year. This project is a reset of a system that had previously been managed for homogeneity and as the results of this study show it will take multiple years of successful disturbance to see an increase in heterogeneity. The results of this study highlight that the patch-burn grazing system is able to have a significant impact on vegetation structure and can potentially increase landscape heterogeneity. Further research is needed in the Nebraska Sandhills to identify how long-term patch-burn grazing systems may increase heterogeneity and how different choices in the implementation of patch-burn grazing such herbivore type, time of burn, grazing intensity and size of burn patches affect the outcome.

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Tables

Table 1. Complete list of all plant species recorded during the 2022 and 2023 survey periods.

Common Name	Sceintific Name
Alsikes Clover	*Trifolium hybridum*
American Bugleweed	*Lycopus americanus*
American Deervetch	*Lotus purshianus*
American Germander	*Teucrium canadense*
Annual Buckwheat	*Eriogonum annuum*
Barnyardgrass	*Echinochloa crus-galli*
Big Bluestem	*Andropogon gerardi*
Bigroot Pricklypear	*Opunita humifusa*
Blazingstar	*Liatris punctata*
Blowout Grass	*Redfieldia flexuosa*
Blue Grama	*Bouteloua gracilis*
Blue Lettuce	*Lactuca pulchella*
Blue Vervain	*Verbena hastata*
Blue-eyed Grass	*Sisyrinchium montanum*
Brittle Cactus	*Opuntia fragilis*
Canadian Goldenrod	*Solidago canadensis*
Clammy Groundcherry	*Physalis heterophylla*
Cudweed Sagewort	*Artemisia ludoviciana*
Curly Dock	*Rumex crispus*
Curlycup Gumweed	*Grindelia squarrosa*
Cutleaf Ironplant	*Machaeranthera pinnatifida*
Daisy Fleabane	*Erigeron strigosus*
Dotted Gayfeather	*Liatris punctata*
Downey Brome	*Bromus tectorum*
Eastern Red Cedar	*Juniperus virginiana*
Field Pennycress	*Thlaspi arvense*
Foxtail Barley	*Hordeum jubatum*
Fringed Puccoon	*Lithospermum incium*
Grassleaved Goldenrod	*Euthamia graminifolia*
Green Sagewort	*Artemisia dracunculus*
Hairy Grama	*Bouteloua hirsuta*
Hemp Dogbane	*Apocynum cannabinum*
Hoary Vervain	*Verbena stricta*
Horseweed	*Conyza canadensis*
Indiangrass	*Sorghastum nutans*
Interior Sandbar Willow	*Salix interior*
Kentucky Bluegrass	*Poa pratensis*
Lambert Crazyweed	*Oxytropis lambertii*
Lamb's Quarter	*Chenopodium album*
Leadplant	*Amorpha canescens*
Leafy Spurge	*Euphorbia esula*
Lemon Scurfpea	*Psoralidium lanceolatum*
Little Bluestem	*Schizachyrium scoparium*
Marsh Fern	*Thelypteris palustris*
Missouri Goldenrod	*Solidago missouriensis*
Prairie Cordgrass	*Spartina pectinata*
Prairie Fameflower	*Phemeranthus parviflorus*
Prairie Junegrass	*Koeleria macrantha*
Prairie Rose	*Rosa arkansana*
Prairie Sandmat	*Euphorbia missurica*
Prairie Sandreed	*Calamovilfa longifolia*
Prairie Violet	*Viola pedatifida*
Prickly Lettuce	*Lactuca serriota*
Purple Lovegrass	*Eragrostis spectabilis*
Purple Poppy Mallow	*Callirhoe involucrata*
Purple Prairieclover	*Dalea purpurea*
Pussytoes	*Antennaria neglecta*
Redtop Bentgrass	*Agrostis stolonifera*
Reed Canarygrass	*Phalaris arundinacea*
Ribseed Sandmat	*Euphorbia glyptosperma*
Rough False Pennyroyal	*Hedeoma hispida*
Rough Horsetail	*Equisetum hyemale*
Roundhead Bushclover	*Lespedeza capitata*
Rush	*Juncus*
Rush Skeletonplant	*Lygodesmia juncea*
Russian Thistle	*Salsola tragus*
Sand Bluestem	*Andropogon hallii*
Sand Dropseed	*Sporobolus cryptandrus*
Sand Lovegrass	*Eragrostis trichodes*
Sand Paspalum	*Paspalum setaceum*
Sandburr	*Cenchrus longispinus*
Scribner's Panic Grass	*Dichanthelium oligosanthes*
Sedge	*Carex*
Manystem Pea	*Lathyrus polymorphus*
Silky Prairie Clover	*Dalea villosa*
Silver Bladderpod	*Lesquerella ludoviciana*
Sixweeksgrass	*Vulpia octoflora*
Slender Greenthread	*Thelesperma simplicifolium*
Small Skullcap	*Scutellaria parvula*
Smooth Brome	*Bromus inermis*
Spiderwort	*Tradescantia occidentalis*
Stiff Sunflower	*Helianthus pauciflorus*
Stiffstem Flax	*Linum rigidum*
Switchgrass	*Panicum virgatum*
Timothy	*Phleum pratense*
Violet Woodsorrel	*Oxalis violacea*
Water Smartweed	*Persicaria amphibia*
Wavy Thistle	*Cirsium undulatum*
Western Ironweed	*Vernonia baldwinii*
Western Ragweed	*Ambrosia psilotachya*

Table 2. Vegetation structural metrics for each field after patch-burn grazing application in 2022 and 2023 to the fields in the North management unit. Mean and standard deviation were calculated from measurements taken at all quadrates located in their respective fields. Fields N5, burned in 2022, and N6, burned in 2023, are in bold.

Mean of Vegetation Structural Metrics

	Vegetation Height (cm)	Litter Depth (cm)	VOR	Bare Ground Cover %	Litter Cover %	Standing Dead Cover %	Forb Cover %	Warm Season Grasses Cover %	Cool Season Grasses Cover %	Shrub Cover %	Sedge spp. Cover %
N5 2022	**27.51**	**0.33**	**2.96**	**29.81%**	**11.79%**	**0.71%**	**17.18%**	**15.07%**	**9.99%**	**5.21%**	**8.21%**
N5 2023	**38.87**	**0.48**	**5.36**	**34.50%**	**20.54%**	**2.80%**	**9.37%**	**24.33%**	**12.75%**	**8.86%**	**7.53%**
N6 2022	**43.30**	**2.89**	**7.08**	**6.16%**	**36.30%**	**31.97%**	**11.45%**	**19.97%**	**13.63%**	**6.76%**	**15.56%**
N6 2023	**42.72**	**1.59**	**6.63**	**20.11%**	**55.22%**	**9.32%**	**9.32%**	**27.83%**	**8.55%**	**7.51%**	**13.71%**
N7 2022	38.20	2.45	5.31	11.54%	35.22%	34.58%	11.94%	15.79%	9.90%	3.33%	11.66%
N7 2023	46.82	2.27	6.71	15.83%	59.38%	11.89%	11.89%	31.70%	6.93%	7.03%	12.36%
N8 2022	34.81	1.97	4.38	10.60%	35.86%	35.79%	9.50%	18.09%	12.41%	5.97%	8.82%
N8 2023	42.08	1.48	5.75	21.13%	38.74%	10.76%	10.76%	26.85%	13.06%	11.70%	7.02%
W1 2022	36.55	1.30	4.38	20.88%	34.17%	33.54%	8.39%	15.14%	9.52%	5.88%	8.90%
W1 2023	35.65	1.50	4.45	21.83%	30.03%	7.41%	7.27%	19.02%	10.63%	6.30%	7.29%
W2 2022	39.31	2.44	4.94	13.35%	39.68%	39.61%	6.79%	18.04%	12.02%	5.45%	10.79%
W2 2023	40.08	2.96	6.54	13.39%	38.12%	11.39%	11.39%	18.64%	11.85%	5.69%	11.82%
W3 2022	45.85	3.04	7.11	12.05%	38.70%	38.65%	12.65%	13.60%	14.12%	3.87%	14.21%
W3 2023	46.55	3.50	6.75	11.55%	37.05%	13.66%	13.66%	16.09%	12.55%	4.91%	14.35%
W4 2022	47.50	2.10	7.27	12.63%	34.59%	34.56%	7.63%	18.50%	10.39%	5.03%	15.56%
W4 2023	46.39	2.20	6.57	12.80%	37.72%	10.41%	10.41%	18.39%	10.25%	4.96%	16.89%

Standard Deviation of Vegetation Structural Metrics

	Vegetation Height (cm)	Litter Depth (cm)	VOR	Bare Ground Cover %	Litter Cover %	Standing Dead Cover %	Forb Cover %	Warm Season Grasses Cover %	Cool Season Grasses Cover %	Shrub Cover %	Sedge spp. Cover %
N5 2022	**14.05**	**0.31**	**3.15**	**20.96%**	**13.47%**	**0.81%**	**13.00%**	**12.54%**	**9.56%**	**9.37%**	**11.32%**
N5 2023	**11.53**	**0.78**	**2.39**	**21.87%**	**27.82%**	**4.06%**	**15.12%**	**21.14%**	**15.64%**	**12.30%**	**10.06%**
N6 2022	**18.90**	**3.13**	**5.50**	**8.61%**	**25.55%**	**25.03%**	**12.39%**	**18.29%**	**13.19%**	**11.12%**	**21.26%**
N6 2023	**18.08**	**1.89**	**4.64**	**23.51%**	**31.57%**	**11.72%**	**11.72%**	**18.85%**	**9.51%**	**11.34%**	**21.33%**
N7 2022	14.47	2.27	2.89	14.98%	22.25%	22.19%	11.31%	13.39%	8.66%	5.16%	17.06%
N7 2023	15.61	1.80	3.27	20.83%	33.72%	12.35%	12.35%	20.05%	8.70%	10.27%	16.33%
N8 2022	10.98	1.81	2.15	12.09%	27.67%	27.75%	7.78%	13.60%	10.40%	10.71%	12.68%
N8 2023	12.80	1.93	1.77	20.39%	29.00%	11.54%	11.54%	18.04%	10.90%	15.82%	11.26%
W1 2022	14.30	1.09	3.33	20.13%	25.60%	25.08%	11.21%	12.79%	8.38%	8.77%	10.63%
W1 2023	12.49	1.08	2.02	23.51%	20.87%	9.20%	9.17%	14.94%	8.04%	11.76%	8.80%
W2 2022	15.41	2.69	2.98	19.52%	30.08%	30.16%	7.78%	15.34%	12.76%	10.03%	15.48%
W2 2023	14.85	3.03	3.65	19.50%	29.33%	13.07%	13.07%	14.75%	12.73%	10.04%	16.77%
W3 2022	16.46	3.49	4.70	15.24%	27.23%	27.30%	14.02%	12.54%	13.58%	6.94%	16.60%
W3 2023	16.05	3.96	3.61	14.87%	22.32%	13.09%	13.09%	13.30%	11.77%	8.35%	16.97%
W4 2022	12.48	2.20	4.44	17.60%	27.34%	27.38%	9.19%	15.24%	13.20%	7.89%	22.64%
W4 2023	12.55	2.22	3.68	17.20%	24.72%	15.50%	15.50%	14.96%	12.83%	7.12%	24.14%

Table 3. Richness and Shannon's Diversity Index of each field after patch-burn grazing application in 2022 and 2023 to fields in the North management unit. The Richness and Shannon's Diversity Index were calculated for each quadrate then the mean and standard deviation were found for each field. Fields N5, burned in 2022, and N6, burned in 2023, are in bold.

	Diversity Metrics			
	Richness		Shannon Diversity Index	
	x̄	σ	x̄	σ
N5 2022	**8.663**	**2.657**	**2.040**	**0.355**
N5 2023	**8.461**	**3.227**	**1.989**	**0.395**
N6 2022	**8.931**	**2.655**	**1.945**	**0.556**
N6 2023	**8.288**	**2.323**	**2.076**	**0.488**
N7 2022	8.688	2.564	2.062	0.394
N7 2023	7.713	2.734	2.156	0.285
N8 2022	7.713	2.734	1.997	0.328
N8 2023	7.750	3.403	2.077	0.260
W1 2022	8.346	2.583	2.033	0.375
W1 2023	9.276	2.965	2.072	0.345
W2 2022	9.588	2.574	1.877	0.489
W2 2023	8.734	2.030	1.834	0.520
W3 2022	8.897	2.431	1.877	0.489
W3 2023	7.525	3.031	1.834	0.520
W4 2022	7.525	3.031	1.843	0.565
W4 2023	7.955	3.203	1.883	0.536

Table 4. Pairwise comparison of fields of interest (N5 and N6) and all other field's vegetation structure using permutational multivariate analysis of variance (PERMNOVA) and a multivariate test for homogeneity of variance (Beta dispersion) in 2022, where N5 was burned that year and N6 would be burned the following year.

June 2022

	PERMNOVA				Beta dispersion		
	Sum of Squares	R2	F	Pr(>F)	F	Pr(>F)	Avg Distance From Mean (x:y)
N5:N6	1.555	0.354	41.631	<0.001 ***	0.693	0.5303	0.161 : 0.178
N5:N7	1.025	0.304	34.127	<0.001 ***	0.914	0.494	0.161 : 0.144
N5:N8	0.729	0.267	28.388	<0.001 ***	5.921	0.0747	0.161 : 0.122
N5:W1	0.397	0.15	13.792	<0.001 ***	2.163	0.27	0.161 : 0.134
N5:W2	2.047	0.441	61.483	<0.001 ***	0.05	0.8241	0.161 : 0.157
N5:W3	1.721	0.417	49.267	<0.001 ***	0.163	0.7597	0.161 : 0.170
N5:W4	2.112	0.504	79.169	<0.001 ***	5.29	0.0784	0.161 : 0.121
N6:N7	0.1	0.036	2.862	0.0684	2.769	0.2171	0.178 : 0.144
N6:N8	0.263	0.102	8.653	<0.001 ***	8.953	0.0378 *	0.178 : 0.122
N6:W1	0.512	0.167	15.267	<0.001 ***	4.448	0.0994	0.178 : 0.134
N6:W2	0.062	0.021	1.612	0.1954	0.945	0.494	0.178 : 0.157
N6:W3	0.036	0.013	0.88	0.3829	0.148	0.7597	0.178 : 0.170
N6:W4	0.094	0.038	2.991	0.0629	8.05	0.0380 *	0.178 : 0.121

August 2022

	PERMNOVA				Beta dispersion		
	Sum of Squares	R2	F	Pr(>F)	F	Pr(>F)	Avg Distance From Mean (x:y)
N5:N6	0.784	0.182	16.947	<0.001 ***	0.037	0.8484	0.184 : 0.178
N5:N7	0.62	0.156	14.369	<0.001 ***	0.147	0.8303	0.184 : 0.175
N5:N8	0.44	0.13	11.633	<0.001 ***	3.912	0.1338	0.184 : 0.137
N5:W1	0.702	0.196	18.955	<0.001 ***	5.515	0.0882	0.184 : 0.126
N5:W2	0.229	0.054	4.457	0.0286 *	0.258	0.7965	0.184 : 0.198
N5:W3	0.929	0.244	22.282	<0.001 ***	1.046	0.5757	0.184 : 0.157
N5:W4	1.534	0.363	44.544	<0.001 ***	8.144	0.0393 *	0.184 : 0.119
N6:N7	0.027	0.009	0.655	0.5236	0.037	0.8484	0.179 : 0.175
N6:N8	0.1	0.036	2.835	0.0803	3.532	0.1387	0.179 : 0.137
N6:W1	0.048	0.018	1.398	0.2678	5.076	0.0882	0.179 : 0.126
N6:W2	0.32	0.079	6.515	0.0063 **	0.537	0.6729	0.179 : 0.198
N6:W3	0.024	0.009	0.605	0.524	0.768	0.6238	0.179 : 0.159
N6:W4	0.136	0.053	4.264	0.0330*	7.973	0.0400 *	0.179 : 0.112

Table 5. Pairwise comparison of fields of interest (N5 and N6) and all other field’s vegetation structure using permutational multivariate analysis of variance (PERMNOVA) and a multivariate test for homogeneity of variance (Beta dispersion) in 2023, where N5 was burned the previous year and N6 was burned that year.

June 2023

	PERMNOVA				Beta dispersion		
	Sum of Squares	R2	F	Pr(>F)	F	Pr(>F)	Avg Distance From Mean (x:y)
N5:N6	0.091	0.03	2.365	0.1206	3.946	0.1315	0.140 : 0.189
N5:N7	0.181	0.075	6.288	0.0136*	0.006	0.9369	0.140 : 0.141
N5:N8	0.141	0.058	4.814	0.0238 *	0.025	0.9369	0.140 : 0.143
N5:W1	0.16	0.073	6.1	0.0136 *	0.295	0.7584	0.140 : 0.128
N5:W2	0.455	0.16	14.85	<0.001 ***	0.218	0.7584	0.140 : 0.150
N5:W3	0.39	0.147	11.879	<0.001 ***	1.034	0.5518	0.140 : 0.164
N5:W4	0.319	0.135	12.13	<0.001 ***	0.308	0.7584	0.140 : 0.128
N6:N7	0.051	0.018	1.387	0.2475	4.522	0.1315	0.189 : 0.141
N6:N8	0.047	0.016	1.273	0.2542	4.075	0.1315	0.189 : 0.143
N6:W1	0.229	0.081	6.736	0.0135 *	7.847	0.0420 *	0.189 : 0.128
N6:W2	0.221	0.07	5.752	0.0160 *	2.875	0.2038	0.189 : 0.150
N6:W3	0.188	0.063	4.489	0.0318 *	0.925	0.5518	0.189 : 0.164
N6:W4	0.158	0.057	4.625	0.0238*	8.149	0.0410 *	0.189 : 0.128

August 2023

	PERMNOVA				Beta dispersion		
	Sum of Squares	R2	F	Pr(>F)	F	Pr(>F)	Avg Distance From Mean (x:y)
N5:N6	0.074	0.037	2.959	0.0829	14.596	0.0018**	0.100 : 0.167
N5:N7	0.279	0.172	16.158	<0.001 ***	2.19	0.2065	0.100 : 0.123
N5:N8	0.026	0.021	1.674	0.209	1.144	0.3719	0.100 : 0.115
N5:W1	0.068	0.048	3.89	0.0528	3.127	0.1315	0.100 : 0.126
N5:W2	0.309	0.118	10.388	<0.001 ***	20.34	0.0003***	0.100 : 0.186
N5:W3	0.117	0.076	5.673	0.0210 *	10.145	0.0094 **	0.100 : 0.152
N5:W4	0.192	0.132	11.869	<0.001 ***	1.024	0.3719	0.100 : 0.115
N6:N7	0.136	0.059	4.755	0.0415 *	5.38	0.0500 *	0.167 : 0.123
N6:N8	0.024	0.012	0.906	0.3698	8.497	0.0152 *	0.167 : 0.115
N6:W1	0.088	0.038	3.043	0.0829	4.681	0.0625	0.167 : 0.126
N6:W2	0.242	0.072	5.861	0.0209 *	0.709	0.4358	0.167 : 0.186
N6:W3	0.053	0.023	1.574	0.2083	0.517	0.4745	0.167 : 0.152
N6:W4	0.106	0.049	3.889	0.053	7.757	0.0175 *	0.167 : 0.115

Figures

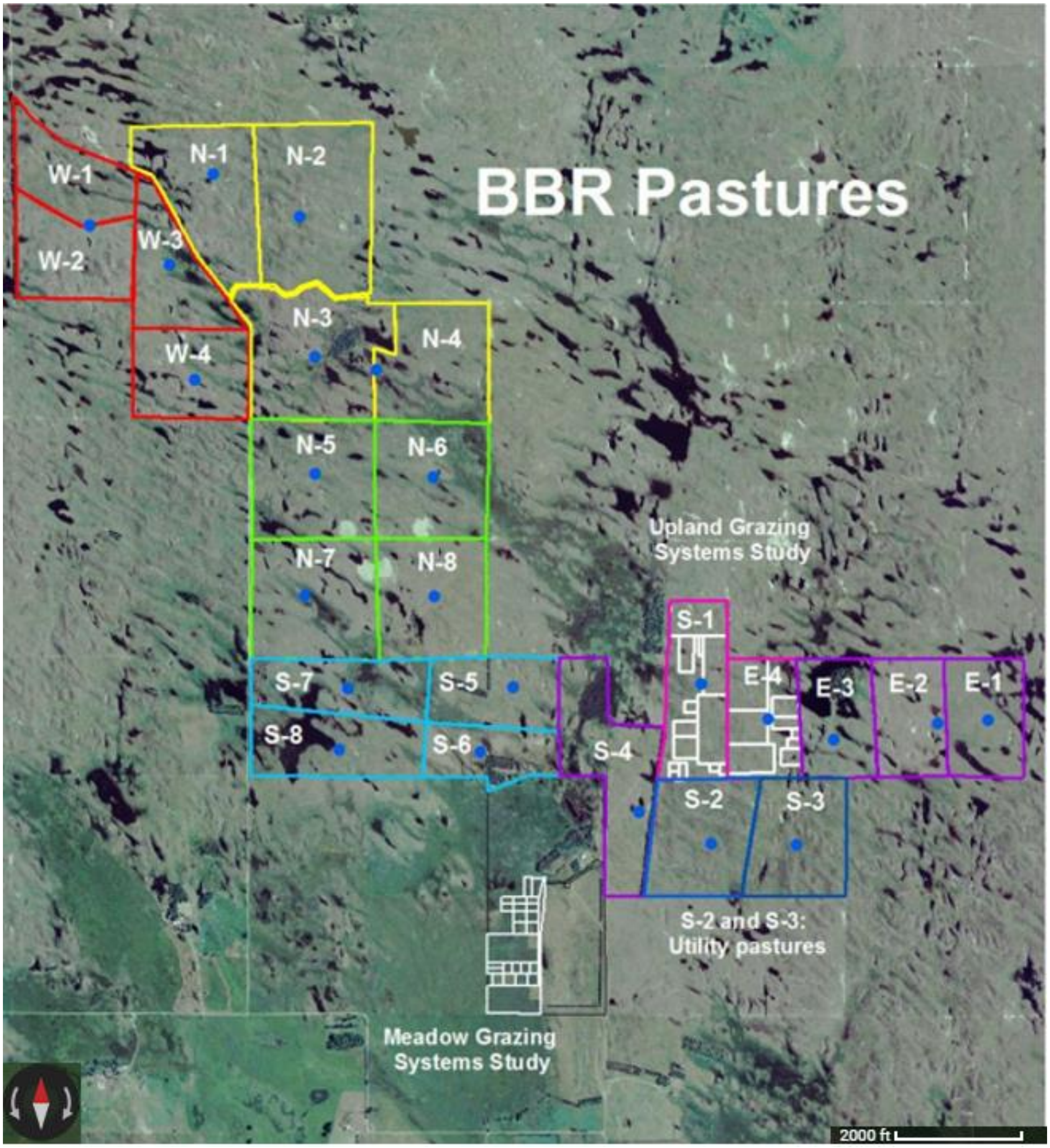
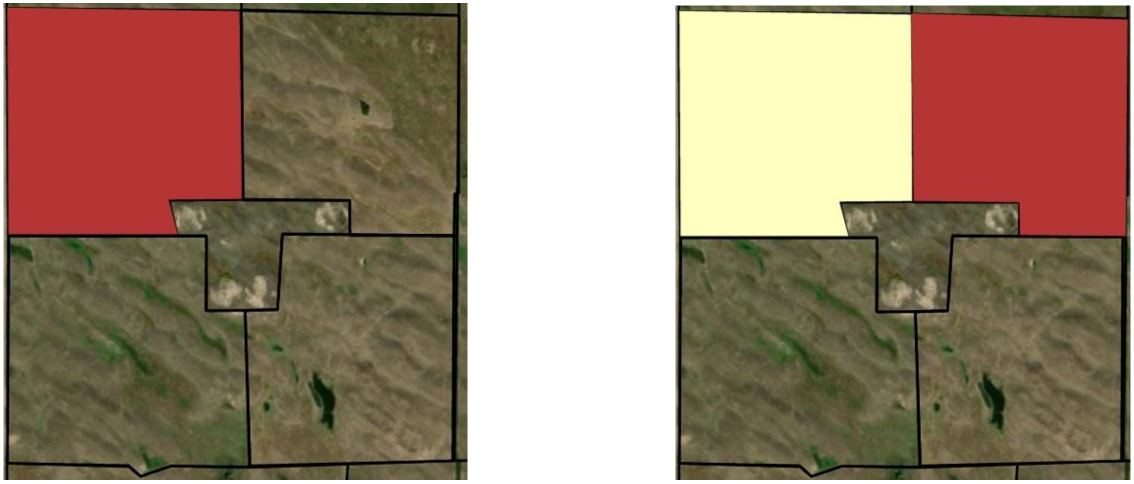
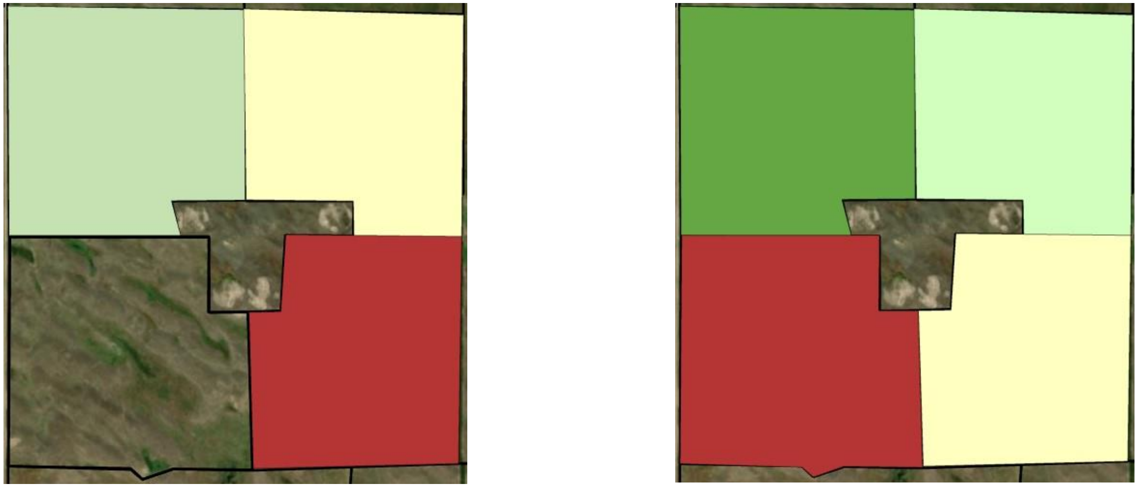


Figure 2. Map of the Barta Brothers Ranch highlighting the different pastures and management units. https://extension.unl.edu/statewide/enre/bbr-pastures-edwards-unit.jpg



(A) 2022 burn in Field N5

(B) 2023 burn in Field N6



(C) Proposed 2024 burn in Field N8

(D) Proposed 2025 burn in Field N7

	2022	2023	2024	2025
N5	Burn	1Y Recovery	2Y Recovery	3Y Recovery
N6		Burn	1Y Recovery	2Y Recovery
N7				Burn
N8			Burn	1Y Recovery
W1	First Rotation	Deferred	Third Rotation	Second Rotation
W2	Second Rotation	Third Rotation	Deferred	First Rotation
W3	Deferred	Second Rotation	First Rotation	Third Rotation
W4	Third Rotation	First Rotation	Second Rotation	Deferred

Figure 3. Management plant for N and W management units at Barta Brothers Ranch in which this study was conducted and where data was collected in the summers of 2022 and 2023. The North unit follows a fire rotation that allows 3 years of recovery for fields between burns. The colors in the table following the burn and recovery plan seen in images A-D. The West unit follows a traditional rational grazing structure with one field deferred every year as seen in the table.

(A) N5 May 2022 Burn

(B) N6 March 2023 Burn

Figure 4. Images taken after the 2022 (A) and 2023 (B) prescribed burns in Fields N5 and N6. The images show the contrast in burn intensity and ability of each burn to remove above ground vegetation.

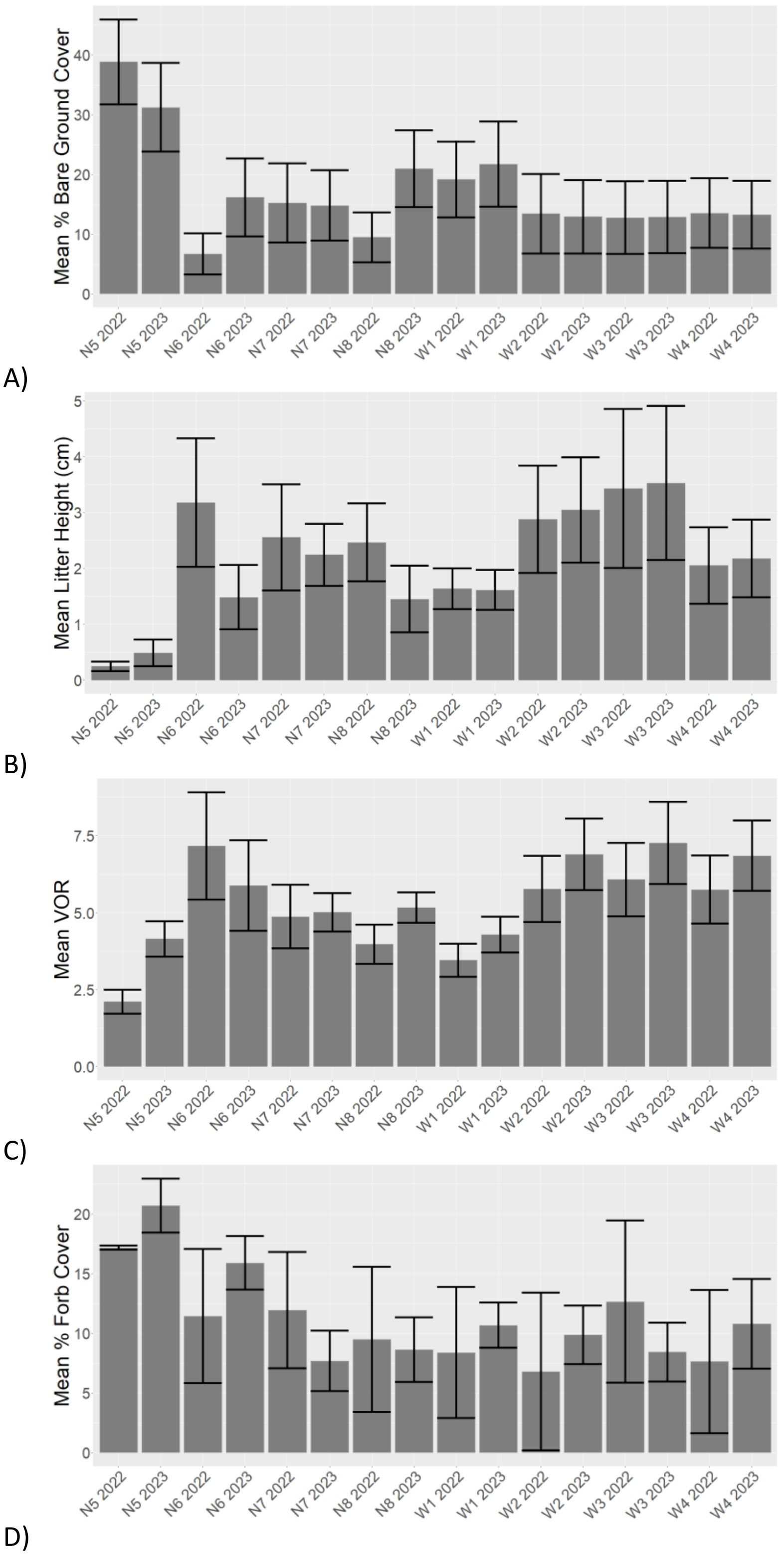
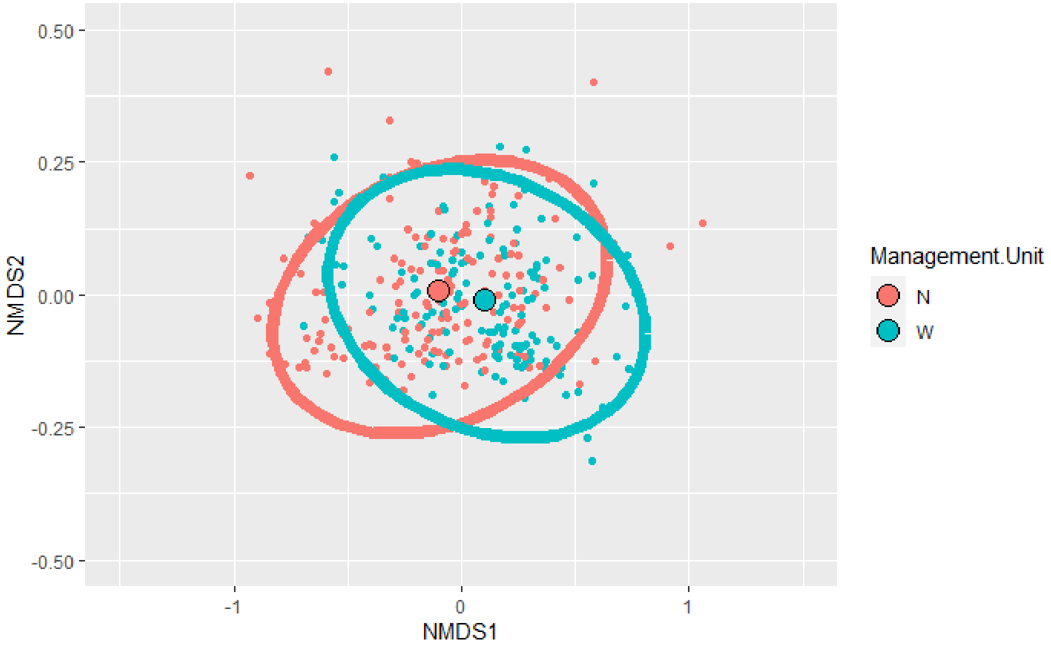


Figure 5. Bar graphs presenting the mean of several structural measurements that were most impacted by treatment for each field in 2022 and 2023 with error bars based on a 0.95 confidence interval. Bare ground cover (A), litter depth (B), visual obstruction (C), and forb cover (D). N5 was burned in 2022 and N6 was burned in 2023.

A. June 2022 Vegetation Structural Metric NMDS for Manament Units
Stress = 0.0618



B. August 2022 Vegetation Structural Metric NMDS for Manament Units
Stress = 0.0543

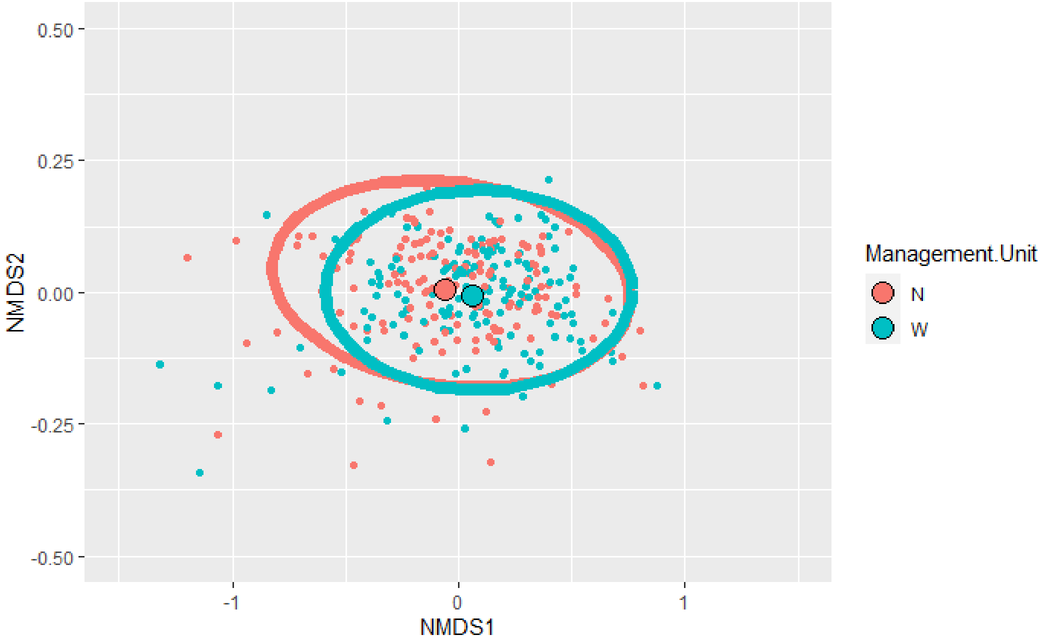
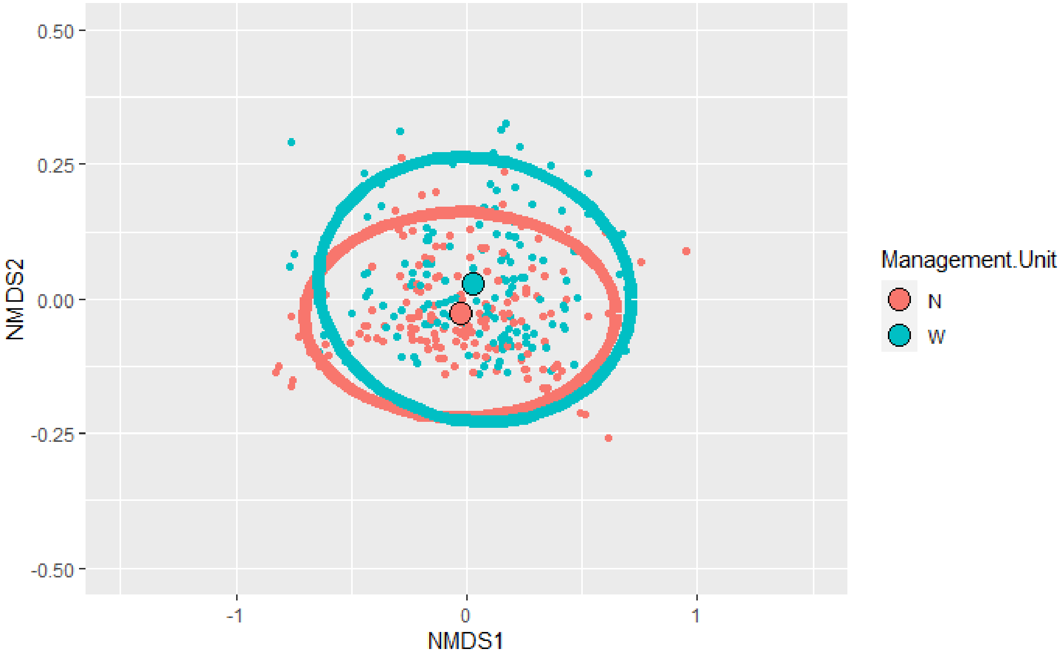


Figure 6. NMDS ordination of vegetation structural metrics in June 2022 (A) and August 2022 (B) at the management unit level. Each ellipse encompasses the normal distribution for the unit with the corresponding color and the large centroids mark the mean position within those groups in the ordination.

A. June 2023 Vegetation Structural Metric NMDS for Manament Units
Stress = 0.0631



B. August 2023 Vegetation Structural Metric NMDS for Manament Units
Stress = 0.0654

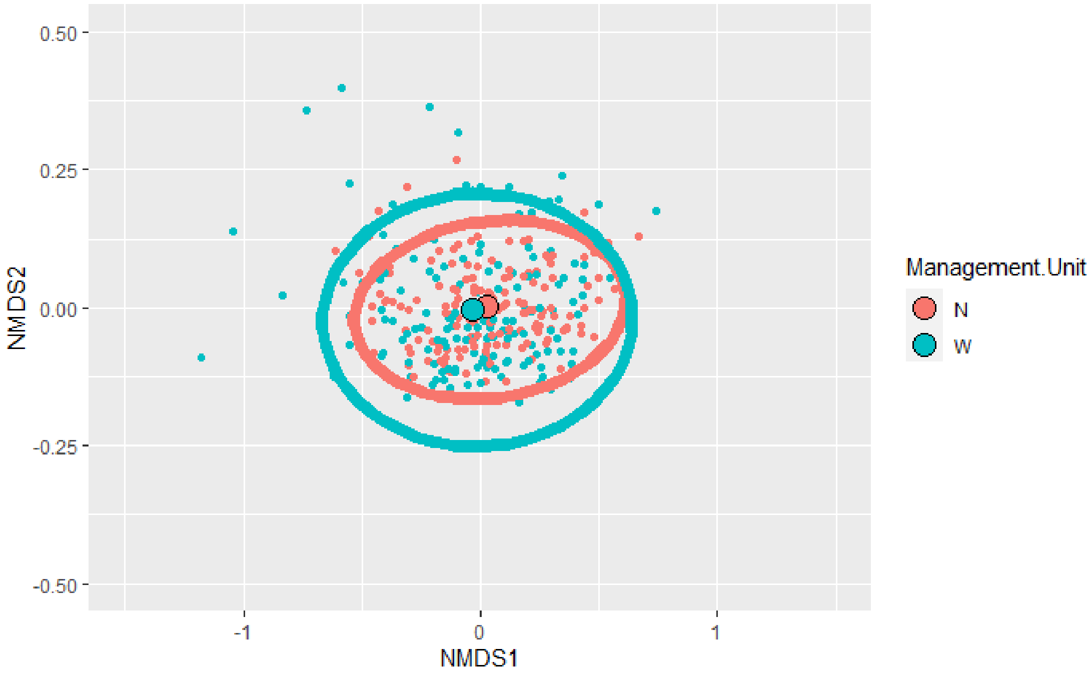
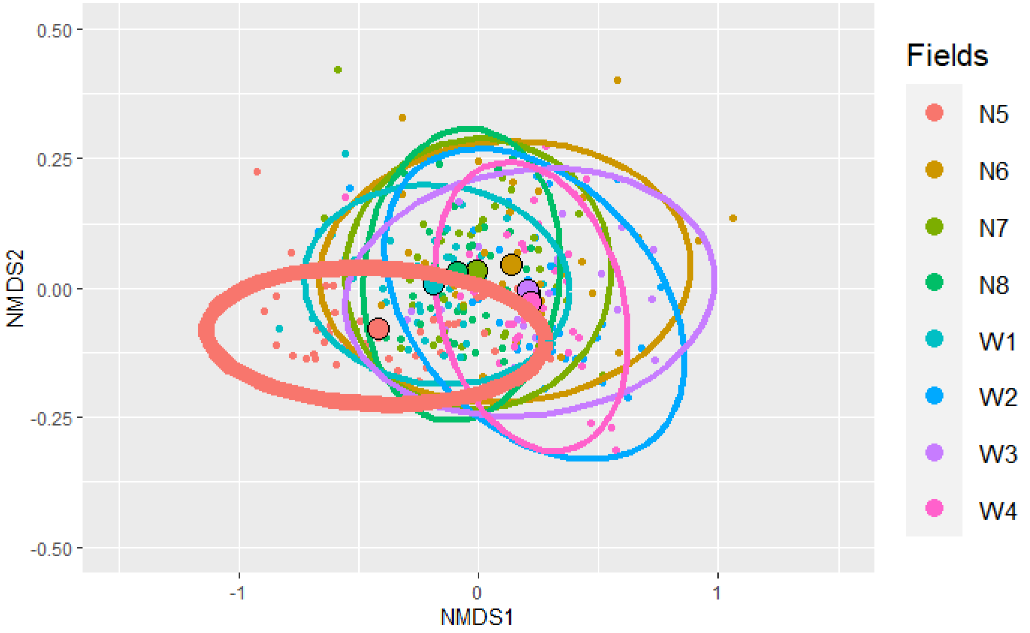


Figure 7. NMDS ordination of vegetation structural metrics in June 2023 (A) and August 2023 (B) at the management unit level. Each ellipse encompasses the normal distribution for the unit with the corresponding color and the large centroids mark the mean position within those groups in the ordination.

A. June 2022 Vegetation Structural Metric NMDS for Fields
Stress = 0.0618



B. August 2022 Vegetation Structural Metric NMDS for Fields
Stress = 0.0543

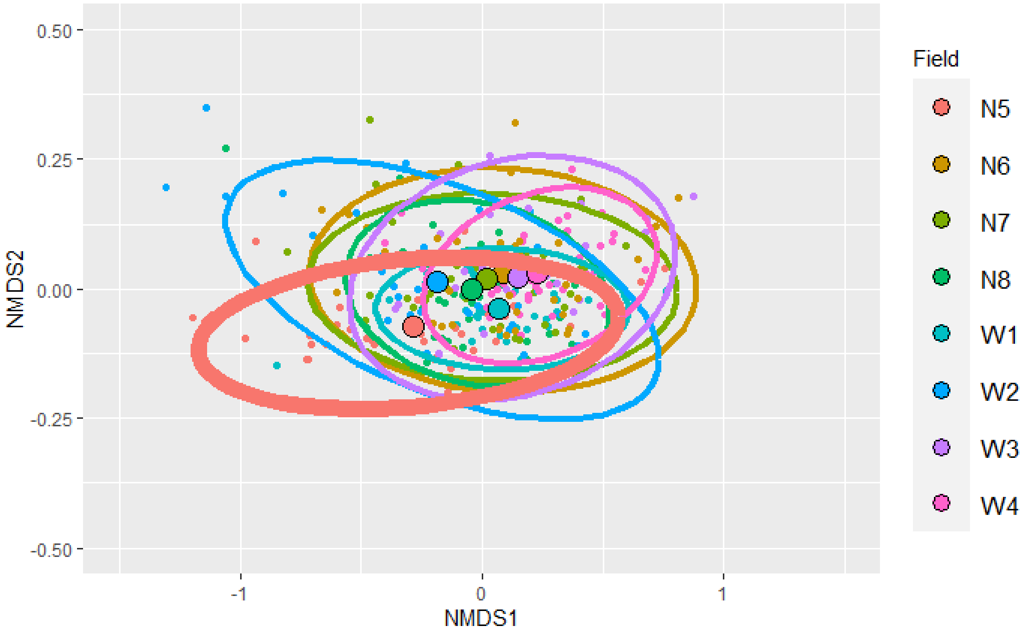
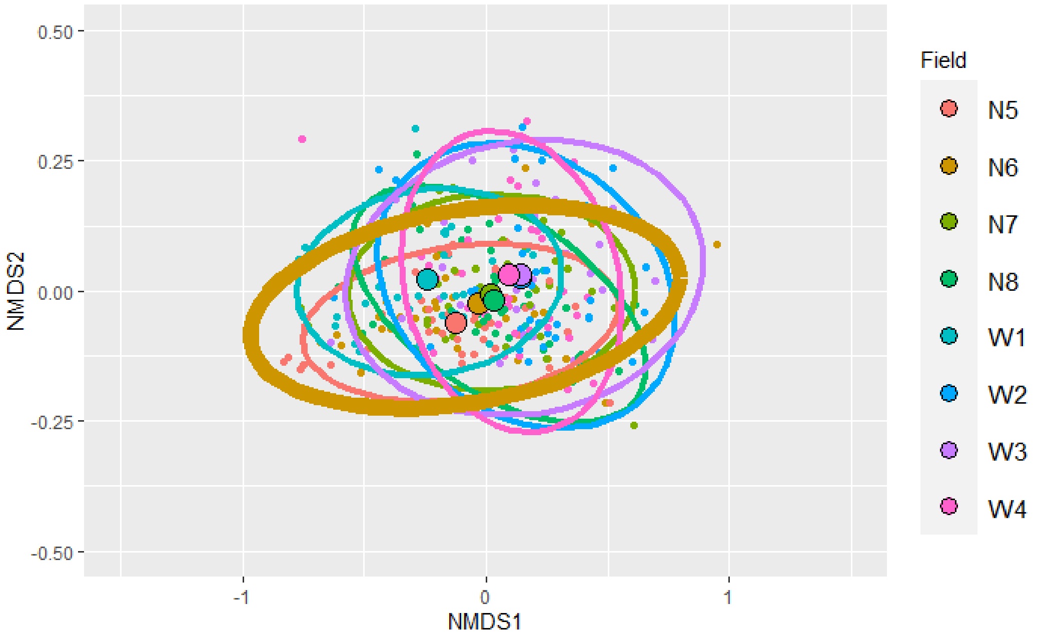


Figure 8. NMDS ordination of vegetation structural metrics in June 2022 (A) and August 2022 (B) at the field level. Each ellipse encompasses the normal distribution for the unit with the corresponding color and the large centroids mark the mean position within those groups in the ordination. The ellipse for field N5 that was burned in 2022 has been thickened to help readers interpret these graphs.

A. June 2023 Vegetation Structural Metric NMDS for Fields
Stress = 0.0631



B. August 2023 Vegetation Structural Metric NMDS for Fields
Stress = 0.0654

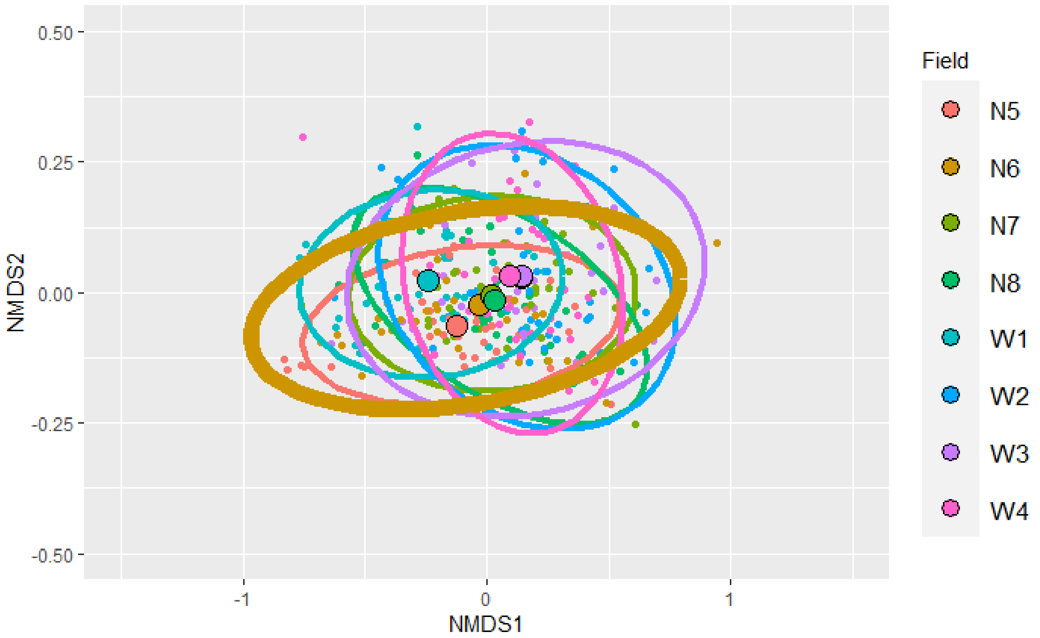
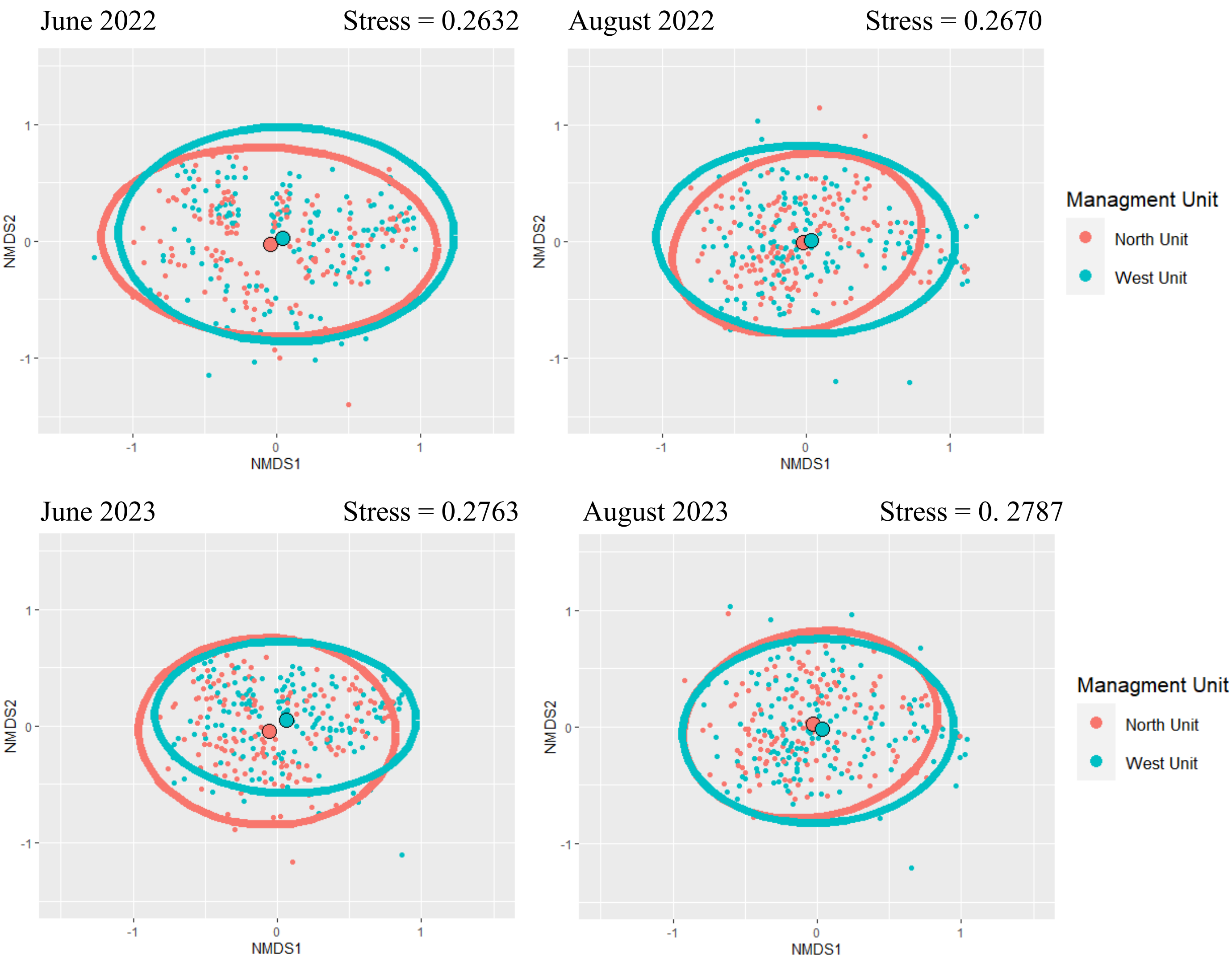


Figure 9. NMDS ordination of vegetation structural metrics in June 2023 (A) and August 2023 (B) at the field level. Each ellipse encompasses the normal distribution for the unit with the corresponding color and the large centroids mark the mean position within those groups in the ordination. The ellipse for field N6 that was burned in 2023 has been thickened to help readers interpret these graphs.



June 2022 Stress = 0.2632

August 2022 Stress = 0.2670

June 2023 Stress = 0.2763

August 2023 Stress = 0. 2787

Figure 10. NMDS ordination of the vegetation community differentiated by management unit. Each ellipse encompasses the normal distribution for the unit with the corresponding color and the large centroids mark the mean position within those groups in the ordination.

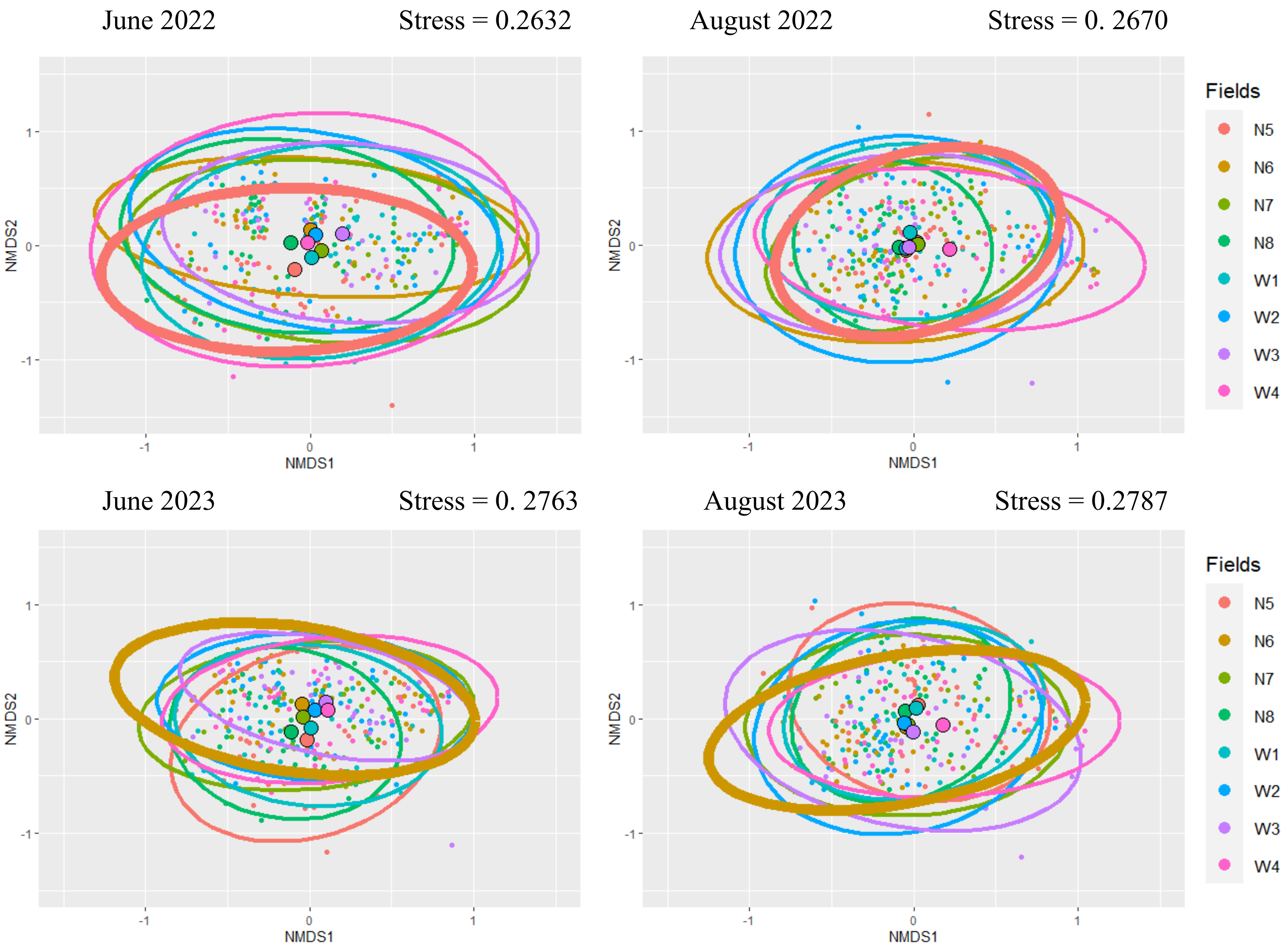
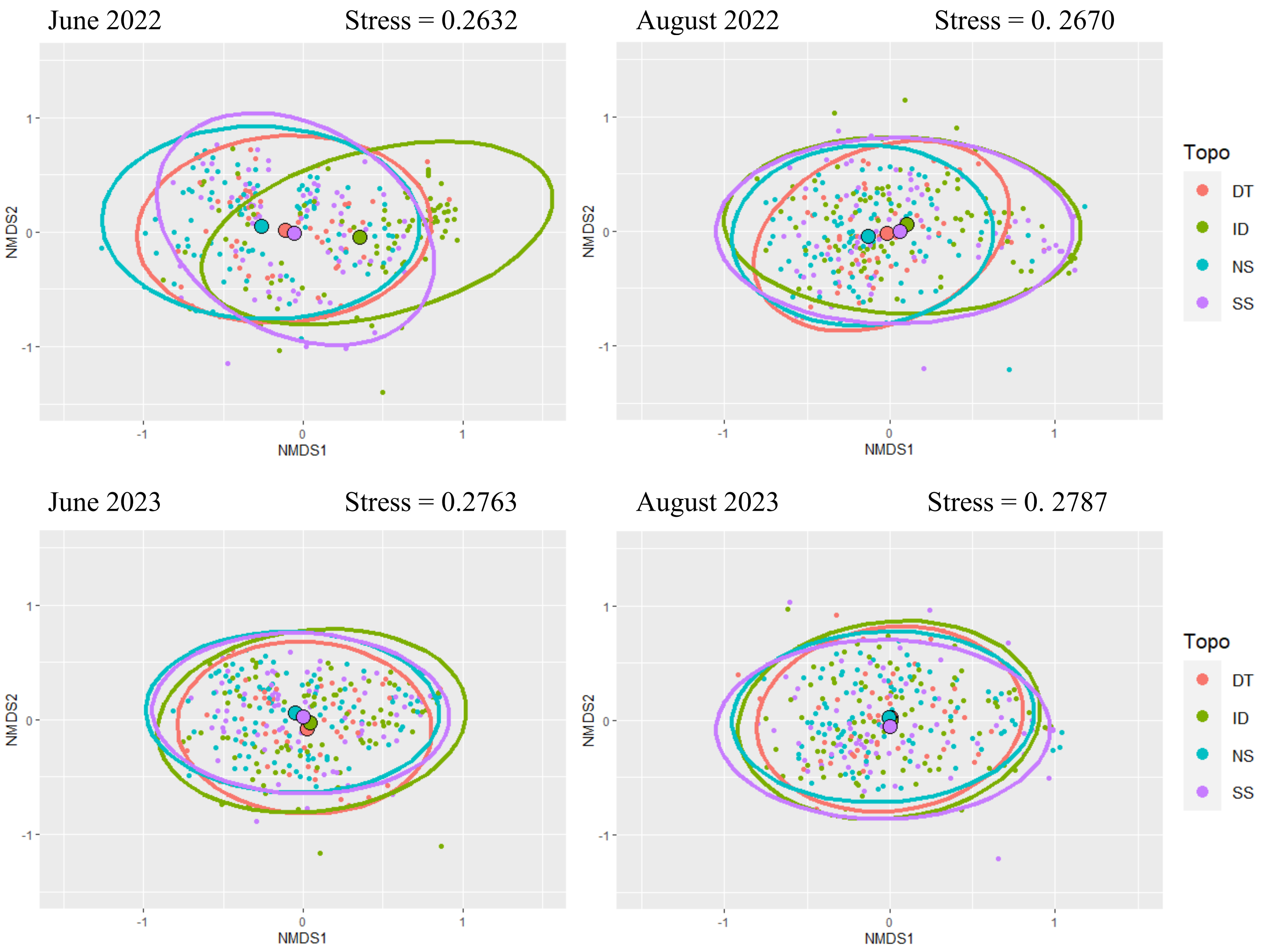


Figure 111. NMDS ordination of the vegetation community differentiated by individual field. Each ellipse encompasses the normal distribution for the unit with the corresponding color and the large centroids mark the mean position within those groups in the ordination. The ellipses of field N5 are thickened in the 2022 graphs and the ellipses of field N6 are thickened in the 2023 graphs to highlight the burned fields of those years.


June 2022 Stress = 0.2632

August 2022 Stress = 0. 2670

June 2023 Stress = 0.2763

August 2023 Stress = 0. 2787

Figure 12. NMDS ordination of the vegetation community differentiated by topographic position on the sand dunes. Each ellipse encompasses the normal distribution for the unit with the corresponding color and the large centroids mark the mean position within those groups in the ordination.

Chapter 4- Grassland Bird Response to Patch-Burn Grazing in the Nebraska Sandhills

Introduction

In the United States dry savanna or steppe, grassy savanna, prairie, and shrub savanna ecosystems have declined by an estimated 98% since European settlement (Bailey 1980, Noss et al. 1995, White et al. 2000, Wilsey et al. 2019). This decline is attributed to habitat degradation, and fragmentation, conversion of native grasslands to non-native grasses and row crop agriculture, fire suppression, and mismanaged livestock grazing (Green et al. 2005, White et al. 2000). Alongside the decline of grasslands in North America, long term studies have shown significant decreases in the populations of grassland bird species, more so than in any other avian guild (Igl and Johnson 1997, Peterjohn and Sauer 1997). Anthropogenic changes to historical disturbance regimes in grasslands may be contributing to these declines (Brennan and Kuvleskey 2005, Askins et al. 2007). The Flint Hills of Kansas and Oklahoma are a core area containing large-scale tracts of intact ecosystems comprised mostly of native plant communities in an otherwise less intact landscape (Maestas et al. 2022). Even this large (2 million ha) and relatively intact region has suffered from continued declines in grassland bird populations due to intensive beef production in the region and its homogenization of the landscape (With et al. 2008).

The Nebraska Sandhills are one of the world’s most intact temperate grasslands regions and are characterized by a semi-arid mixed grass prairie with rolling grass-stabilized sand dunes and are surrounded by some of the least intact grassland ecoregions (Scholtz & Twidwell 2022). In the Sandhills a fear of destabilization and a desire for better rangeland conditions for cattle production led to tight control of wildfires and changes in land management practices in the early

1900's (Stubbendieck et al. 1989, Holechek et al. 1989). Livestock producers in the Sandhills shifted management to discourage highly disturbed areas by using uniform moderate grazing and rest periods (Holechek et al. 1989). In grasslands, disturbance-driven heterogeneity has long been minimized in favor of "managing for the middle" which promotes using uniform grazing distribution (Twidwell et al. 2013, Fuhlendorf et al. 2012). This is in opposition to the recognition of the importance of disturbance driven spatial and temporal patterns critical to the sustainability and maintenance of ecosystems. Biological diversity is proceeded by heterogeneity and therefore it should be the basis for ecosystem management and conservation (Wiens 1997, Fuhlendorf and Engle 2001, Fuhlendorf et al. 2006). Disturbances, such as fire, interact across the landscape with differential timing and correspond with successional stages among patches that create heterogenous conditions known as a shifting mosaic (Fuhlendorf & Engle 2004). Grassland birds have evolved in association with the dynamic disturbance patterns that shape their habitats, food, and predator communities (Samson et al. 2004, Fuhlendorf et al. 2006, Derner et al. 2009). Studies have shown increasing support for the idea that management for vegetation heterogeneity is important for sustaining grassland avian diversity in semi-arid grasslands (Davis 2005, Lusk and Koper 2013).

Patch-burn grazing has been introduced in many mesic and semi-arid grassland systems as a way to implement a pyric-herbivory disturbance interaction that will increase heterogeneity and support the avian communities and greater diversity within them (Augustine & Derner 2015, Skagen et al. 2018, Powell 2008). Patch-burn grazing is a system that utilizes prescribed fire to burn different portions of a unit each year while allowing cattle to have access to both the burned and unburned areas of the unit. Cattle show a significant preference and utilization of recently burned areas leaving other sections to recover. As different sections are burned it shifts the cattle's grazing focus and creates a shifting mosaic of vegetation structure (Weir et al. 2013). The Nebraska Sandhills has a history of suppressing fire, and many producers still view fire as unsafe to be used in management (Sliwinski et al. 2018). Because of this fire is not often used as a management tool and the response of avian communities in the Sandhills to the use of controlled fire in a patch-burn grazing system has not been explored.

At the University of Nebraska-Lincoln's Barta Brothers Ranch in the Nebraska Sandhill's a Collaborative Adaptive Management (CAM) project has implemented prescribed fire through a patch-burn grazing system with the goal of reducing woody encroachment, increasing heterogeneity and biodiversity in the system and evaluating the economic and ecological trade-offs produced from the patch-burn grazing system (Martens 2023). Prescribed fires were conducted in 2022 and 2023 as part of this project and will continue in the future. This study examines the response of the avian communities to the patch-burn grazing system in relation to the vegetation structure resulting from the burns. Similar studies in other semi-arid grassland regions found that patch-burn grazing help sustain a diversity of breeding habitats, especially for shortgrass birds such as Horned Lark (*Eremophila alpestris*) and Thick-billed Longspur (*Rhynchophanes mccownii*), and in combination with other strategies that retain taller-structured vegetation, semi-arid grasslands are able to support a full range of grassland bird communities. Patch-burn grazing is expected to have a positive impact on avian diversity, and provide habitat for shortgrass species allowing them to have an increased abundance in recently burned patches while species that prefer denser, taller vegetation will decline in these areas but still be supported in unburned or recovering fields.

Methods

This study took place at the University of Nebraska-Lincoln Barta Brothers Ranch in the Eastern Nebraska Sandhills (lat 42°13’32”N, long 99°38’09”W: elevation=765) containing approximately 2,400 hectares of rangeland. The property contains a mix of plant species typically found in the Sandhills region characterized by a mixed-grass prairie. The landscape consists of a mix of sub-irrigated meadows and wetlands making up 10% of the study area with the remaining 90% of the area classified as upland range (Schacht et al. 2000). The study site received an average of 505 mm of precipitation yearly from 2020-2023 with a mean annual temperature for this period of 11°C (HPRCC 2023). Soils at the site are characteristic of Sandhills soils, classified as Valentine fine sands (mixed, mesic Typic Ustipsamments) featuring a low water holding capacity and a high risk of wind erosion (USDA-NRCS 2007).

The Barta Brothers Ranch contains 6 management units that have historically been grazed in a traditional rotational grazing system (Figure 1). In this study, the North management unit (N unit) of fields N5-N8 is the treatment unit for patch-burn grazing and the West management unit (W unit) of W1-W4 acts as a control unit to compare the results of patch-burn grazing to traditional rotational grazing. Fields in both units ranged in size from 57 to 65 hectares and were stocked with spayed heifer cattle at approximately 0.65 AUM ha^{-1} (Martens 2023). Patch-burn grazing was implemented in this study by burning the entirety of a field in the N unit and allowing cattle to have access to the whole unit, including the recently burned field, by way of open gates to allow cattle to preferentially graze. Each year a new field will be burned in rotation, allowing three years of recovery before a field is burned again. The W unit will follow a traditional rotational grazing system (Figure 2). Field N5 was burned in March of 2022 and field N6 was burned in May of 2023. The fire in N5 resulted in a much more complete burn than in

N6 due to its later timing and the weather on that day. By burning in March, higher quantities of green vegetation and a higher humidity caused the burn to be more inconsistent (Figure 3). Cattle were released into both units in May of both years with cattle in the W unit rotated between fields every 1-2 months.

In June of 2022 and 2023, the avian communities in management units N and W were sampled alongside vegetation structural measurements. Avian data was collected using point counts in each field. Point counts were established in locations with clear lines of sight over the majority of the area comprising the point count. Each point count was established at least 150m away from all other points to ensure a closed sample. They were also established at least 150m from all fence lines, tree lines, and tree stands to limit the influence of edge species and maintain a focus on grassland birds. Each field contains five point counts spaced to meet these standards (Figure 4). Field W4 contains only four point counts due to its smaller available size and multiple tree-stands within the field. At each point a surveyor recorded every bird seen or heard within a six-minute time period. All birds found within 100m of the point were reported as inside the count. Any bird seen or heard outside of 100m was recorded but will not be considered in the analysis. Point counts were conducted in the mornings between sunrise and four-hours past sunrise on days with favorable weather conditions defined as no rain, limited cloud and fog cover, and winds below 16 $km \cdot h^{-1}$. Counts were conducted at each point three times each year for a total of six visits over two years, alternating between observers for each point's count. Throughout the analysis of the avian community data, counts taken at the same point during different years are treated as independent points as grassland birds are shown to have low site fidelity rates (Winter et al. 2005).

At each point count a stratified sampling design was used to collect vegetation structure measurements with a 100 x 20 cm frame at eight locations around the center of the point count. In each of the cardinal directions at 37.5m and 75m the frame was placed on the ground to select the plot of vegetation to be measured. Plant height was recorded by measuring the tallest plant in the plot from the base of the plant to the tallest point on that plant. Litter depth was measured at three locations inside of the plot and averaged. Visual obstruction readings (VOR) were measured at each frame using Robel pole with increments of 2.5cm. VOR measurements were taken from four directions around the point at a distance of 4m and a height of 1m. The first increment from the bottom to be 50% obscured was recorded. The four measurements were averaged for the point (Robel et al. 1970). The percent of bare ground cover, litter cover, standing dead vegetation cover, warm season grasses cover, cool season grasses cover, forbs cover, shrub cover, and Carex spp. (Sege spp.) cover were visually estimated within each frame and recorded in the following increments: 0%, > 0 to <1%, 1 to 5%, 6 to 25%, 26 to 50%, 51 to 75%, 76 to 95%, > 95%. The midpoint of each of these cover classes were used in the analysis when comparing cover (Daubenmire 1959).

Species diversity was analyzed by calculating the Shannon's Diversity index (Shannon's H) for each sample. The largest number of observations of each species over the three counts completed at a point was used as an approximate abundance for this calculation. The Shannon's H values calculated for each point in each year were averaged to find a Shannon's H for each field in each year. Because an analysis of the variance model identified a significant difference in the Shannon's H values between fields the following pairwise comparison was used to identify between which fields there was a significant difference in diversity.

Nonmetric multidimensional scaling (NMDS), a distanced based ordination technique, was used to visually describe differences in avian communities. This analysis did not include waterfowl, or those species not observed at least four times through the study or not seen in at least 5% of bird count points (<2) to avoid influence by rare outlier species. A pairwise comparison using permutational multivariate analysis of variance (PERMNOVA) was used to test for significant differences between the avian community of each field. For this analysis, 2022 and 2023 point counts were grouped together into their respective fields, as preliminary analysis did not show differences in communities between 2022 and 2023. Using the *envfit* function of R package vegan (R Core Team 2022, Oksanen et al. 2016), vegetation structural measures along sites with the maximum correlation to the positioning of avian communities in the analysis were identified and fit over the plotted NMDS to show the relationship between avian communities and vegetation structure.

The avian data was collected over three repeated visits within a season so that *N-mixture* modeling could be used to estimate abundance in relationship to the vegetation structural measurements (Royle 2004). The seven avian species of interest that had sufficient data to attempt an analysis of their abundance were the Grasshopper Sparrow (*Ammodramus savannarum*), Western Meadowlark (*Sturnella neglecta*), Horned Lark (*Eremophila alpestris*), Dickcissel (*Spiza americana*), Lark Sparrow (*Chondestes grammacus*), Field Sparrow (*Spizella pusilla*), and Upland Sandpiper (*Bartramia longicauda*). The first four species are included in the Breeding Bird Survey's list of grassland birds, and the following two are considered scrub-dependent species. The final species is a ground-nesting shore bird common to the Sandhills. Of these only the Western Meadowlark, Grasshopper Sparrow, and Dickcissel were successfully modeled. The other species contained too much variability, resulting in low detection probabilities and gross overestimations of abundance. The vegetation structural measurements of interest as covariates of abundance were plant height, litter depth, VOR, % bare ground cover, % litter cover, % standing dead vegetation cover, % warm season grasses cover, % cool season grasses cover, % forbs cover, % shrub cover, and % Sege spp. cover. Four models were made for each species of interest. Three of the models contained the eleven structural measurements at the point, field, and management unit level. Each of these models also contained Julian day on which the counts took place, observer, and minutes after sunrise as covariates in the detection portion of the model to improve accuracy. The fourth model was a null model. Poisson distribution was used for the Western Meadowlark while the Zero-Inflated Poisson distribution was used for the Grasshopper Sparrow and Dickcissel. Distributions were selected by comparing the model fit (AIC) of the null models for each species. The negative-binomial distribution was not used for any species as early analysis showed an unstable response to K (carrying capacity of the population) and inflated abundance estimations. The goodness-of-fit for each species top models were tested with a parametric bootstrap procedure using the *Nmix.gof.test* function in package AICcmodavg with a $p > 0.05$ indicated adequate fit. 85% confidence intervals were used to select variables that were strong predictors of bird abundances (Royle 2004, Fiske and Chandler 2011).

Results

A total of 41 avian species were identified over the course of this two-year study. Grasshopper Sparrows (589 observations), Western Meadowlarks (383 observations), Brown-headed Cowbirds (306 observations), and Red-winged Blackbird (234 observations) were the topmost sighted species throughout the study and accounted for 72% of all observations. Another species of interest, the Horned Lark, was observed 66 times throughout the study, 50 of which observations were located in field N5 (Table 1). Field N7 during 2022 was the most diverse field with a Shannon's H of 2.024 and field W1 in 2023 was the least diverse field with a Shannon's H of 0.77 (Table 2). The analysis of the variance model for Shannon's H between fields was significant (p-value < 0.001). Field W1 tended to be the lowest in 2022 and was significantly lower than N7 and N8 in 2022. In 2023, W1 was significantly lower than all N unit fields besides N7 2023. W2 and W4 2023 were also significantly lower than many of the N fields in both years and W fields in 2022 (Tabel 2). There was a drop in diversity from 2022 to 2023 over most of the fields of which a few were found to be significant. This drop affected the W fields the most while N5 and N6 had a slight but not statistically significant increase.

The NMDS ordination plot in Figure 9 A. shows considerable overlap between avian communities in the different fields, indicated by the overlapping ellipses. The spacing of the centroids indicates that there may be some differences between the mean community composition though. Centroids for fields N6, N7, and W3 are clustered together while the others appear to be separated on their own. The results of the PERNOVA show that the average community of field N5 is significantly different than all other fields. Fields N6, N7, and W3 do not have any support to find them significantly different from each other but N6 is significantly different from all but those two. The only other field not significantly different from N7 is W4. N8 is significantly different from all but W2. Lastly, no support is shown for a significant difference between W2 and W3 as well as W3 and W4 (Table 2). N5 is mostly associated with species such as the Horned Lark, Mourning Dove, Common Nighthawk, Upland Sandpipers and Eastern Kingbirds. This coincides with a much higher % bare cover than any other field (Figure 8). N6, N7, and W3 are mostly associated with species such as Red-wing Blackbird, Bobolink, and Dickcissel that tend to be found in wetland type environments. Wetland environments typically have taller denser vegetation with a larger composition of sedge species which can be seen in N6 and W3 (Figure 7 & 8). Figure 10 confirms this association between these vegetation metrics and the bird communities associated with these fields by their close positioning in the NMDS plot. N6 also has a few sites that are positioned closer to communities similar to N5 and in 2023 a lower litter depth and VOR as well as greater bare ground cover compared to 2022. W4 seems to have similar communities to the three clustered fields but contains many more Grasshopper Sparrows which were the dominant species in that field (Table 1). N8 and W2 are the two fields most associated with the scrubland species such as Lark Sparrow and Field Sparrow. These fields visibly contained the most Easter Redcedar encroachment.

Two of the three species abundances that were estimated with the N-mixture models responded to some vegetation structure, Western Meadowlark and Dickcissel. The Grasshopper Sparrows did not respond to any of the vegetation characteristics (null model was the top model *w*=0.99; Table 5). Western Meadowlark abundance was best explained by vegetation measurements at the field level (*w*=0.88; Table 5). There was some evidence to suggest that bare ground cover was related to their abundance (Table 6) with a slight decrease in abundance the more bare ground was present but with wide confidence intervals towards both extremes of the estimates (Figure 11). Dickcissel abundance was also best explained by vegetation measurements at the field level but failed the goodness-of-fit test (*w*=0.9, p-value = 0.013; Table 5). Instead, the next best model, explaining Dickcissel abundance by vegetation measurements at the management unit level, was used. In this model, the evidence shows that Dickcissel abundance was related to cool and warm season grass cover, shrub cover, and litter cover. Similar decreases in abundance were seen as both cool season and shrub cover increased. Abundance saw an increase as both warm season and litter cover increased (Figure 10).

Discussion

Patch-burn grazing is being introduced to the Nebraska Sandhills as a way to increase the resilience of the ecosystem by increasing heterogeneity and biodiversity as it has been shown to do in other grassland ecosystems (Fuhlendorf et al. 2009, Fuhlendorf & Engle 2004). Following the 2022 fire in field N5 and the 2023 fire in field N6, a clear visual change was seen in the burned grassland that was reflected in the collected vegetation measurements (Figures 8&9). This in turn had a clear effect on the avian communities living in these fields. The findings of this study support the prediction that a patch-burn grazing system would have a positive impact on the avian community by creating a wider diversity in habitat for a wider diversity of grassland bird species.

The study saw the field burned in 2022, N5, develop a different avian community compared to other fields in the patch-burn grazing system and the control system. Bird species favoring bare ground and less dense vegetation were more common there than in any other field. In particular the Horned Lark was almost exclusively found in this field. Following the 2023 burn in N6 some individuals were observed in N6, but the majority were still found in N5. The less intense response in field N6 following the 2023 could be attributed to the less intense, patchy burn of that year. Without a complete burn, the change in vegetation structure was not on a large enough scale to attract a noticeably different community of bird species.

Between the two years of this study there was a noticeable decrease in diversity between 2022 and 2023. The W control unit saw the most decrease with several fields being significantly lower than the previous year and fields from the N unit. In the N unit, only N7 and N8 decreased. The two burned fields, N5 and N6, both saw slight increases in their diversity. In the spring leading up to the 2023 survey the eastern half of Nebraska containing the study area, experienced a severe short-term drought and recorded one of the driest springs ever. From April to May precipitation was between 5% - 50% of normal precipitation (HPRCC 2023). Continuous or periodic extreme droughts have been shown to cause changes in the abundance of avian species (Roberts et al. 2021, Albright et al. 2010). The disturbance of the drought could explain the drop in diversity seen in 2023 and patch-burn grazing could explain why communities in the patch-burn grazing unit were better able to weather this disturbance.

The abundance models that responded to vegetation measurements both responded primarily at the field level. This contradicts recent recommendations to manage grassland bird habitat at larger scales (Walk and Warner 2000, Greer et al. 2016). This could be explained by the management actions in these first two years having only taking place at the field level whereas in the following years, patch-burn grazing will have been applied across the whole unit. Grasshopper Sparrows were ubiquitous throughout the study cite and did not respond to any vegetation variables. Their profuse presence is consistent with an area that has been regularly managed with light or moderate conservative grazing strategies (Sutter & Richison 2005). Meadowlarks are usually seen as a generalist habitat preference (Davis and Lanyon 2008) and this was seen as they also had a ubiquitous presence throughout the study but there was a slight decrease with an increase in bare ground indicating that the patch-burn grazing is having an effect.

While this study shows that patch-burn grazing may be used as an effective management tool to promote avian communities, there are several limitations. This study was limited to only the first two years of the application of the patch-burn grazing system. More distinct differences between the treatment unit and the control would be expected after a full rotation of the patch-burn grazing system, as it creates a more mosaic like heterogeneous landscape. Another limitation of this study is its focus on the disturbance driven heterogeneity. The Nebraska Sandhills possesses innate heterogeneity that was not quantified in this study but the impact of which could be seen in the results. The impact of factors such as the percent of landscape composition covered by wetland areas, or the abundance of Eastern Red Cedar (*Juniperus virginiana*) can be seen in what type of avian communities were present in the different fields. For example, a large portion of field N6 is covered by a large wetland resulting in a large composition of wetland bird species, and fields N8 and W2 had an abundance of Eastern Red Cedar present while simultaneously having higher presence of scrubland dependent bird species. Future studies need to consider this subject over a longer time period and take into consideration how the innate heterogeneity of the landscape will impact the results. Additionally, this study was completed with only one treatment group and one control. As the use of fire as a management tool becomes more widespread in the Sandhills, the impact that it has on the avian communities should be studied with a larger sample size to support and expand upon the findings of this study.

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Tables

Table 1. List of bird species recorded during the 2022 and 2023 surveys in each field and as a total. The number of observations are not indicative of true abundance as they were collected as part of three repeated visits to each point and so would be an overestimate of abundance.

Species	Scientific Name	N5	N6	N7	N8	W1	W2	W3	W4	Total Observations
Grasshopper Sparrow	Ammodramus savannarum	50	70	97	82	103	65	43	79	589
Western meadowlark	Sturnella neglecta	66	32	61	42	38	54	38	52	383
Brown-headed Cowbird	Molothrus ater	45	21	48	51	32	54	22	33	306
Red-winged Blackbird	Agelaius phoeniceus	31	56	47	2	3	9	54	32	234
Upland Sandpiper	Bartramia longicauda	21	14	16	7	5	9	10	9	91
Field Sparrow	Spizella pusilla	2	5	5	35	6	23	4	5	85
Dickcissel	Spiza americana	3	10	37	4	0	1	8	10	73
Horned Lark	Eremophila alpestris	50	5	1	4	4	0	0	2	66
Lark Sparrow	Chondestes grammacus	10	6	2	19	1	5	0	4	47
Bobolink	Dolichonyx oryzivorus	1	15	17	0	0	0	3	4	40
Mourning Dove	Zenaida macroura	7	6	7	3	0	8	2	4	37
Eastern Kingbird	Tyrannus tyrannus	2	2	2	1	0	4	6	5	22
American Goldfinch	Spinus tristis	0	2	4	8	0	2	3	0	19
Blue-winged Teal	Anas discors	6	4	3	0	0	0	4	0	17
Common Nighthawk	Chordeiles minor	5	3	0	2	1	0	0	0	11
Common Yellowthroat	Geothlypis trichas	0	9	0	1	0	1	0	0	11
Greater Prairie Chicken	Tympanuchus cupido	2	1	1	1	1	1	1	1	9
Yellow Warbler	Setophaga petechia	0	1	0	2	0	3	2	0	8
Barn Swallow	Chlidonias niger	0	0	3	0	0	0	0	3	6
Brown thrasher	Toxostoma rufum	0	0	1	2	0	1	2	0	6
Mallard	Anas platyrhynchos	3	0	1	0	0	0	2	0	6
Wilson's Snipe	Gallinago delicata	0	4	1	1	0	0	0	0	6
Loggerhead Shrike	Phasianus colchicus	0	0	0	0	0	5	0	0	5
Gadwall	Mareca strepera	2	0	0	0	0	0	1	1	4
Killdeer	Charadrius vociferus	3	0	0	0	0	0	0	1	4
Black Tern	Chlidonias niger	0	0	0	0	0	0	2	1	3
Red-headed woodpecker	Melanerpes erythrocephalus	0	0	0	3	0	0	0	0	3
Wood duck	Aix sponsa	0	0	0	2	0	0	0	1	3
Blue Grosbeak	Anas discors	0	0	0	0	0	1	2	0	3
American Crow	Corvus brachyrhynchos	0	0	0	1	0	1	0	0	2
American Robin	Turdus migratorius	0	0	0	1	1	0	0	0	2
Bell's Vireo	Vireo bellii	0	0	0	1	0	0	1	0	2
Chipping Sparrow	Spizella passerina	0	1	0	0	1	0	0	0	2
Common Grackle	Quiscalus quiscula	1	0	0	0	0	1	0	0	2
Orchard Oriole	Icterus spurius	0	0	0	0	0	0	2	0	2
Sedge Wren	Cistothorus stellaris	1	1	0	0	0	0	0	0	2
Long-billed Curlew	Cistothorus stellaris	1	0	0	0	0	0	0	0	1
Ringed-neck Pheasant	Phasianus colchicus	0	0	1	0	0	0	0	0	1
Tree Swallow	Tachycineta bicolor	0	1	0	0	0	0	0	0	1
Vesper Sparrow	Aix sponsa	0	0	0	1	0	0	0	0	1
Yellow-headed Blackbird	Cardinalis cardinalis	0	0	1	0	0	0	0	0	1

Tabel 2. Results of the pairwise t-test comparison of each field's Shannon Diversity Index. The resulting p-values were adjusted using the Bonferroni correction to reduce false positive findings. Bold indicates a significance of at least the 0.05 level.

	H index	N5 2022	N5 2023	N6 2022	N6 2023	N7 2022	N7 2023	N8 2022	N8 2023	W1 2022	W1 2023	W2 2022	W2 2023	W3 2022	W3 2023	W4 2022
N5 2022	1.658	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
N5 2023	1.738	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
N6 2022	1.576	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-
N6 2023	1.763	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-
N7 2022	2.024	1	1	1	1	-	-	-	-	-	-	-	-	-	-	-
N7 2023	1.512	1	1	1	1	1	-	-	-	-	-	-	-	-	-	-
N8 2022	1.892	1	1	1	1	1	1	-	-	-	-	-	-	-	-	-
N8 2023	1.208	1	1	1	1	1	1	0.348	-	-	-	-	-	-	-	-
W1 2022	1.027	0.689	0.242	1	0.172	**0.003**	1	**0.0268**	1	-	-	-	-	-	-	-
W1 2023	0.770	**0.019**	**0.005**	**0.065**	**0.004**	**0.00005**	0.161	**0.0004**	1	1	-	-	-	-	-	-
W2 2022	1.819	1	1	1	1	1	1	1	1	1	1	-	-	-	-	-
W2 2023	0.875	0.089	**0.028**	0.279	**0.019**	**0.0003**	0.645	**0.002**	1	1	1	**0.008**	-	-	-	-
W3 2022	1.763	1	1	1	1	1	1	1	1	0.307	**0.009**	1	**0.041**	-	-	-
W3 2023	1.354	1	1	1	1	0.689	1	1	1	1	1	1	1	1	-	-
W4 2022	1.819	1	1	1	1	1	1	1	0.892	0.079	**0.002**	1	**0.008**	1	1	-
W4 2023	0.847	0.059	**0.018**	**0.19**	**0.012**	**0.0001**	0.45	**0.002**	1	1	1	**0.005**	1	**0.028**	1	**0.005**

Table 3. Pairwise comparison of avian community in all fields using permutational multivariate analysis of variance (PERMNOVA). Significant p-value indicates a significant difference in mean community composition of the fields.

	R2	F	Pr(>F)		R2	F	Pr(>F)
N5:N6	0.148	3.116	0.0180*	N7:W1	0.383	11.165	0.0004***
N5:N7	0.243	5.772	0.0007***	N7:W2	0.225	5.229	0.0007***
N5:N8	0.362	10.218	0.0004***	N7:W3	0.126	2.298	0.065
N5:W1	0.378	10.920	0.0006***	N7:W4	0.079	1.536	0.1771
N5:W2	0.295	7.519	0.0004***	N8:W1	0.288	7.286	0.0005***
N5:W3	0.275	6.069	0.0006***	N8:W2	0.095	1.895	0.0865
N5:W4	0.226	5.269	0.0006***	N8:W3	0.303	6.953	0.0014**
N6:N7	0.091	1.811	0.1224	N8:W4	0.237	5.591	0.0004***
N6:N8	0.280	6.999	0.0006***	W1:W2	0.162	3.492	0.04*
N6:W1	0.356	9.955	0.0004***	W1:W3	0.385	10.017	0.0004***
N6:W2	0.225	5.221	0.0004***	W1:W4	0.136	2.841	0.0487*
N6:W3	0.116	2.101	0.0742	W2:W3	0.210	4.250	0.002*
N6:W4	0.148	3.139	0.0181*	W2:W4	0.114	2.326	0.0742
N7:N8	0.339	9.223	0.0006***	W3:W4	0.123	2.236	0.0812

Table 4. Results of function *envfit* from R package vegan indicating the vegetation measurements best explain difference in the to avian species community structures when fitted as vectors on the avian community NMDS ordination. The r^2 measures goodness of fit and " * " indicates a significant variable.

Vegetation Measurements	r^2	Pr(>r)
Plant Height	0.1345	0.008**
Litter depth	0.1123	0.015*
VOR	0.2457	0.001***
% Bare Ground Cover	0.1243	0.005**
% Litter Cover	0.0067	0.801
% Standing Dead Cover	0.0117	0.656
% Forb Cover	0.0267	0.373
% Warm Season Cover	0.0478	0.167
% Cool Season Cover	0.0467	0.16
% Shrub Cover	0.0443	0.174
% Sedge Cover	0.1663	0.001***

Table 5. Model selection table for the relationship between the abundance of Grasshopper Sparrows, Western Meadowlarks, and Dickcissels and the vegetation structural measures at three scales (point, field, management unit). Models are order for each species according to the Akaike's Information Criterion corrected for small sample sizes (AICc) reported with the difference in AICc from the best ranking model, model weight (*w*), log-likelihood (LL) and the Chi-square goodness of fit p-value from a parametric bootstrap procedure.

Models	AICc	Δ AIC	*w*	LL	Chi-squar p-value
Grasshopper Sparrow					
Null	794.88	0	0.99	-394.277	0.998
Field	815.19	20.31	0.00	-382.044	
Point	819.89	25.01	0.00	-384.394	
Unit	833.73	38.85	0.00	-391.313	
Western Meadow Lark					
Field	709.69	0	0.88	-331.05	1
Point	713.76	4.07	0.11	-333.084	
Unit	718.84	9.15	0.01	-335.623	
Null	744.83	35.14	0.00	-370.34	
Dickcissel					
Field	288.11	0	0.98	-118.503	0.013
Point	296.15	8.04	0.02	-122.525	0.696
Unit	320.74	32.63	0.00	-134.82	
Null	326.78	38.67	0	-160.225	

Table 6. Parameter estimates (β) and standard errors (SE) for the response of the bird species abundance response to vegetation structure measurements. Abundance covariates are on the log-scale. Western Meadowlarks and Dickcissels responded to vegetation structure measurements averaged across the field level. Grasshopper Sparrows did not respond to any vegetation structure measurements. Bold text indicates that the 85% confidence intervals did not overlap zero.

	Western Meadowlark Field Model			Dickcissel Field Model			Grasshopper Sparrow Null Model		
Abundance Covariates	β	SE	p-value	β	SE	p-vale	β	SE	p-value
(Intercept)	1.924	3.275	0.557	0.106	1.515	0.944	1.830	0.185	<**0.001**
Bare Ground Cover	0.050	0.032	**0.124**	-0.012	0.035	0.732	-	-	-
Litter Depth (cm)	0.232	0.585	0.692	0.177	0.209	0.396	-	-	-
Standing Dead Cover	0.005	0.039	0.893	0.014	0.016	0.376	-	-	-
Cool Season Grass Cover	-0.015	0.425	0.971	-0.062	0.031	**0.046**	-	-	-
Warm Season Grass Cover	0.042	0.113	0.710	0.041	0.025	**0.098**	-	-	-
Forb Cover	-0.034	0.167	0.841	0.029	0.030	0.326	-	-	-
Shrub Cover	-0.128	0.091	0.162	-0.155	0.070	**0.027**	-	-	-
Plant Height (cm)	0.012	0.162	0.940	-0.018	0.025	0.486	-	-	-
VOR	-0.025	0.791	0.975	0.087	0.102	0.395	-	-	-
Litter Cover	-0.005	0.094	0.956	0.028	0.011	**0.012**	-	-	-

Figures

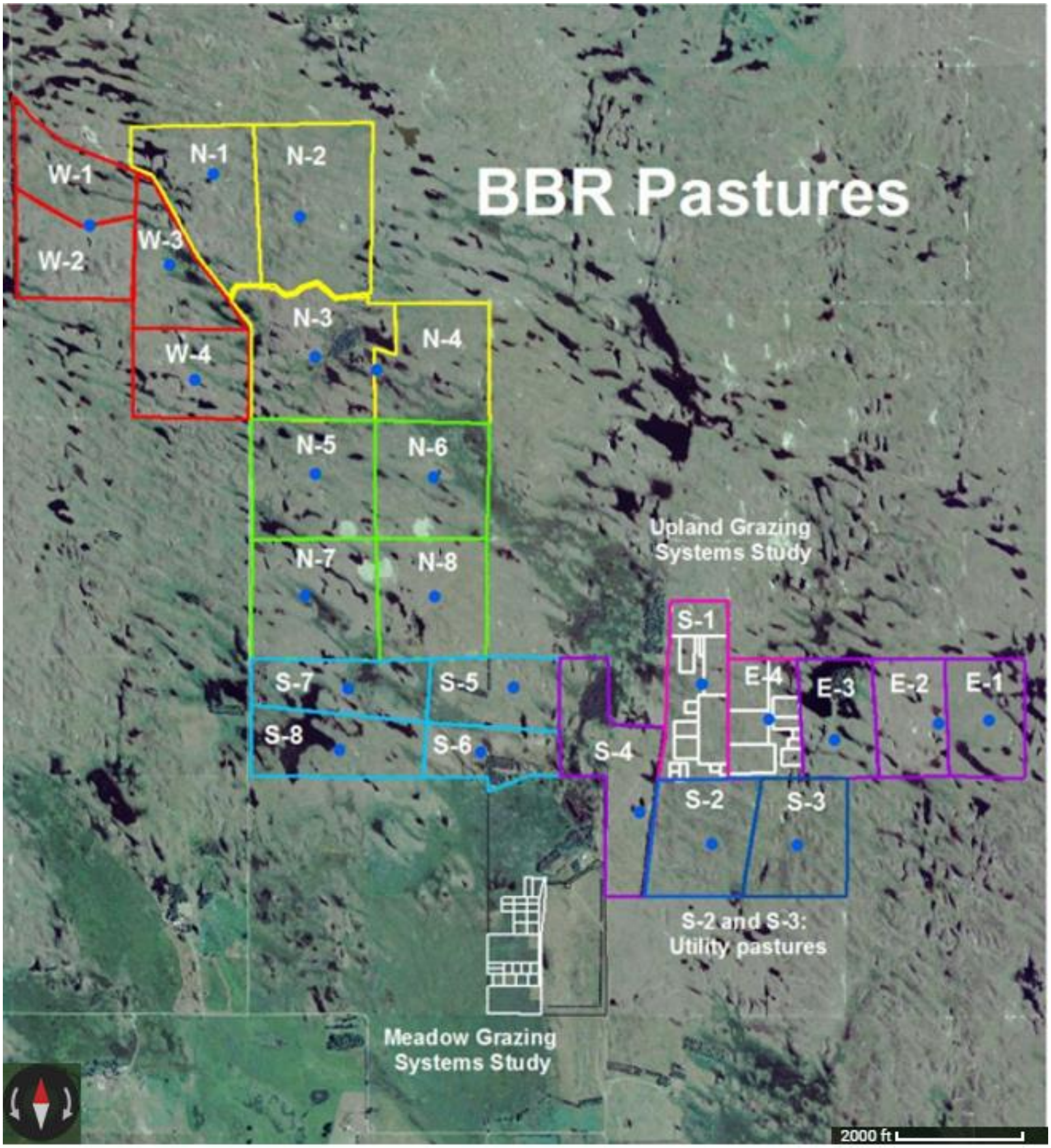
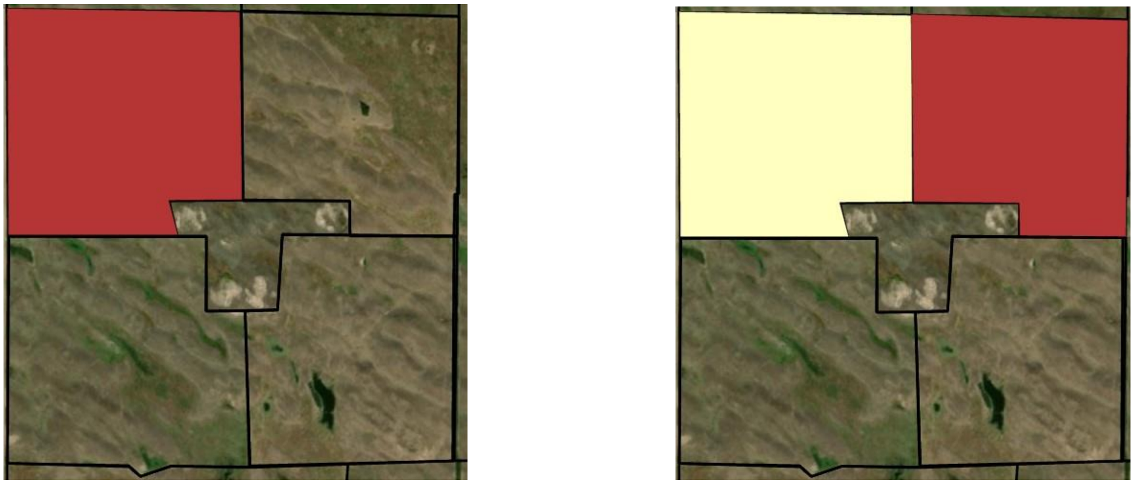
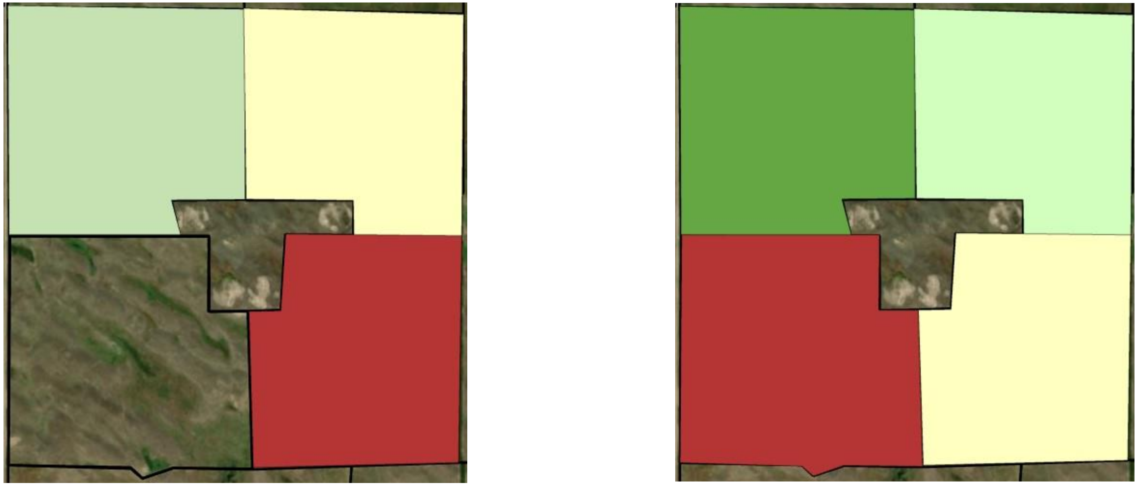


Figure 1. Map of the Barta Brothers Ranch highlighting the different pastures and management units. https://extension.unl.edu/statewide/enre/bbr-pastures-edwards-unit.jpg


(A) 2022 burn in Field N5

(B) 2023 burn in Field N6


(C) Proposed 2024 burn in Field N8

(D) Proposed 2025 burn in Field N7

	2022	2023	2024	2025
N5	Burn	1Y Recovery	2Y Recovery	3Y Recovery
N6		Burn	1Y Recovery	2Y Recovery
N7				Burn
N8			Burn	1Y Recovery
W1	First Rotation	Deferred	Third Rotation	Second Rotation
W2	Second Rotation	Third Rotation	Deferred	First Rotation
W3	Deferred	Second Rotation	First Rotation	Third Rotation
W4	Third Rotation	First Rotation	Second Rotation	Deferred

Figure 2. Management plant for N and W management units at Barta Brothers Ranch in which this study was conducted and where data was collected in the summers of 2022 and 2023. The North unit follows a fire rotation that allows 3 years of recovery for fields between burns. The colors in the table following the burn and recovery plan seen in images A-D. The West unit follows a traditional rational grazing structure with one field deferred every year as seen in the table.

(A) N5 May 2022 Burn

(B) N6 March 2023 Burn

Figure 3. Images taken after the 2022 (A) and 2023 (B) prescribed burns in Fields N5 and N6. The images show the contrast in burn intensity and ability of each burn to remove above ground vegetation.

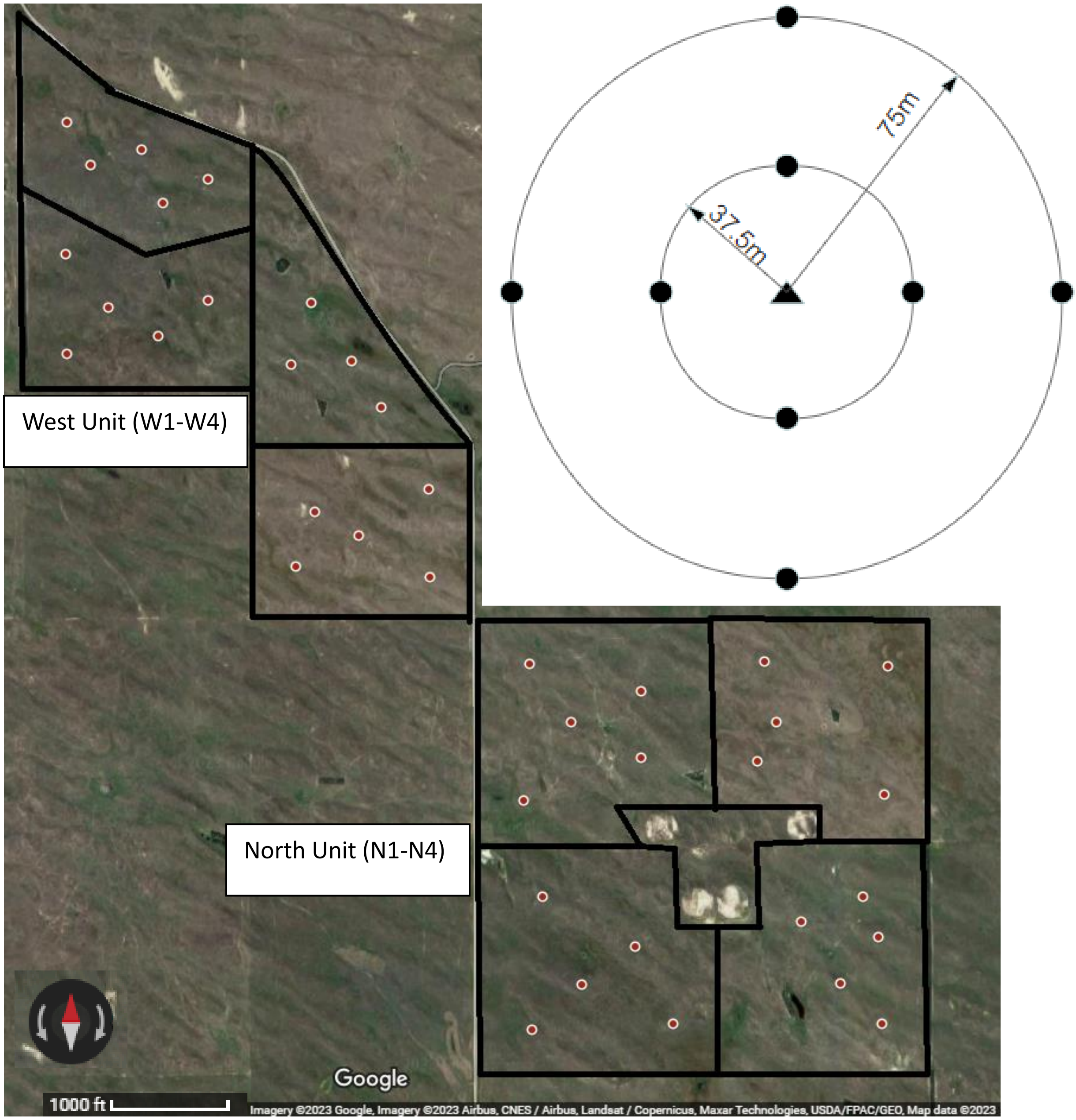
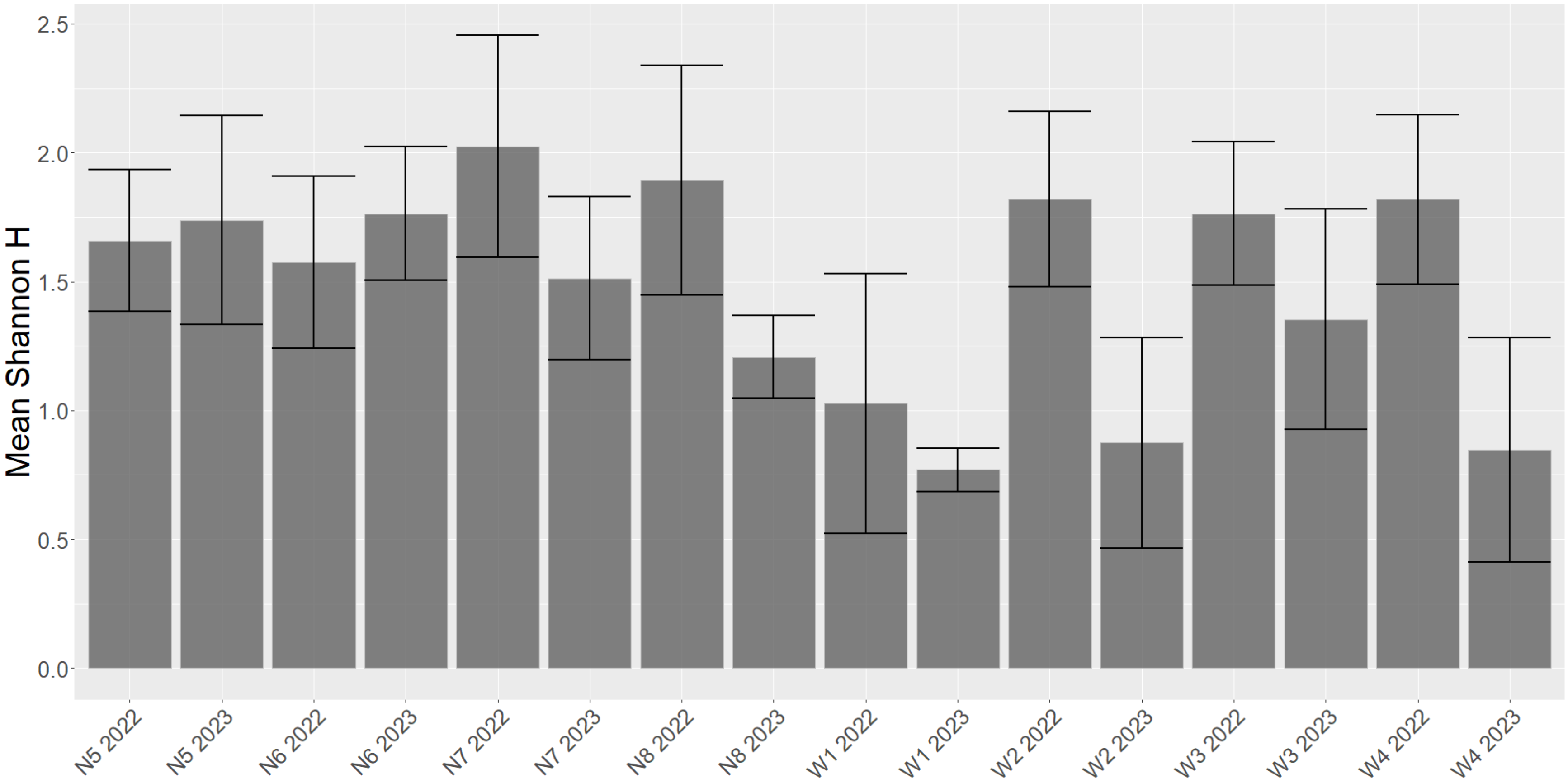


Figure 4. Map of Barta Brothers treatment and control units showing position of bird point counts in each field and a diagram of a point counts showing the sampling design for the vegetation structure measurements. The triangle in the center is where the point count is preformed from, and the circles indicate where frames were placed in the four cardinal directions at 37.5m and 75m distances from the center.

Figure 5. Graph chart showing trends in the mean Shannon's Diversity Index (H) of each field in 2022 and 2023 with error bars based on a 0.95 confidence interval. Prescribed fire treatment took place in field N5 during 2022 and field N6 in 2023.



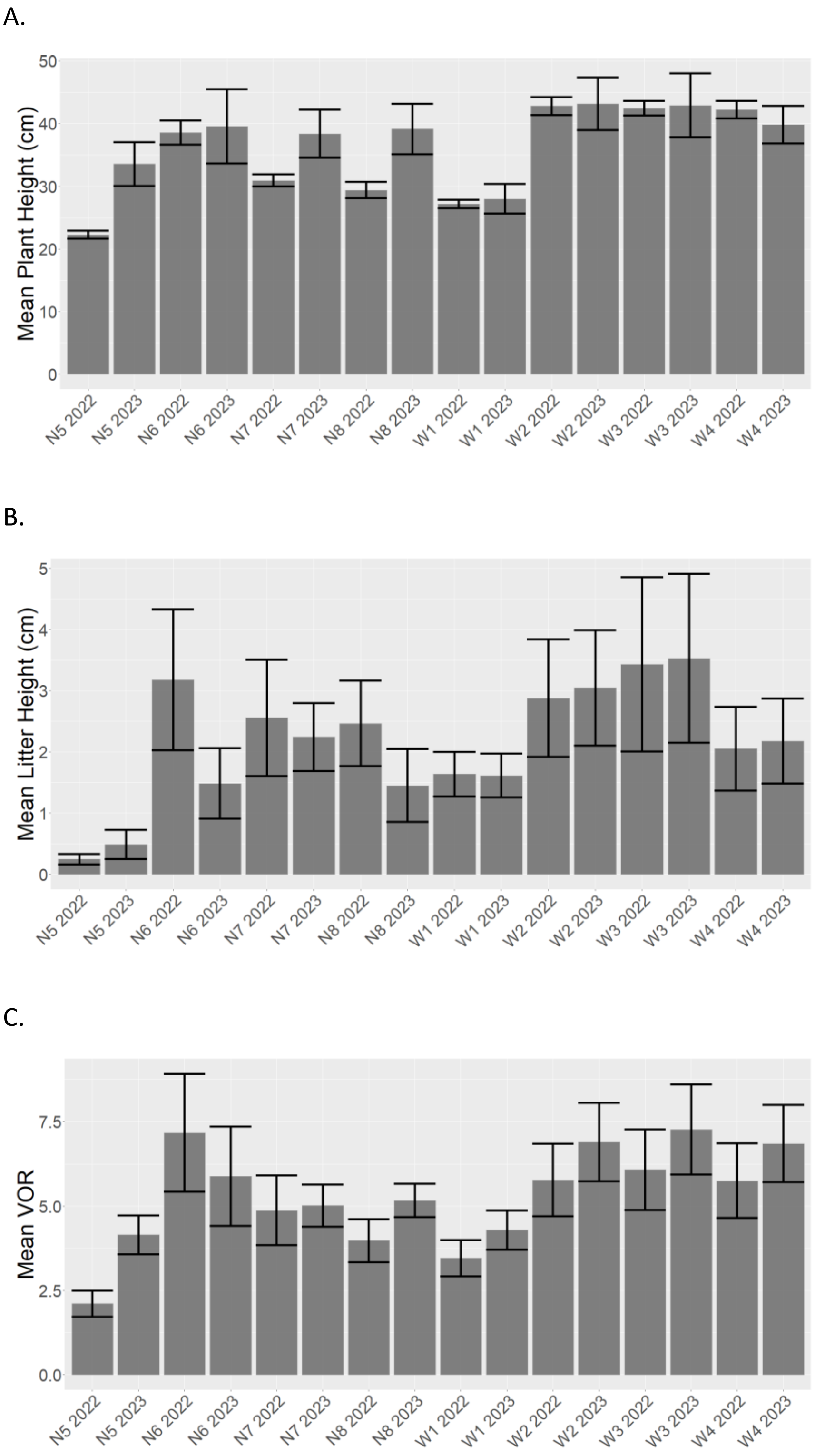
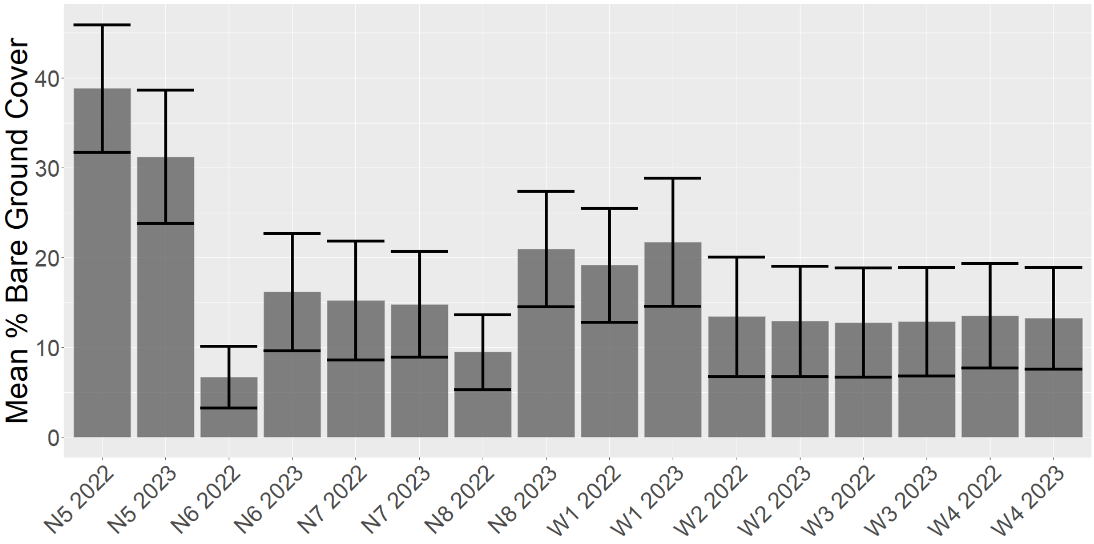


Figure 6. Bar graphs present the mean plant height (A), litter depth (B), and visual obstruction (C) of each field in 2022 and 2023 with error bars based on a 0.95 confidence interval.

A



B

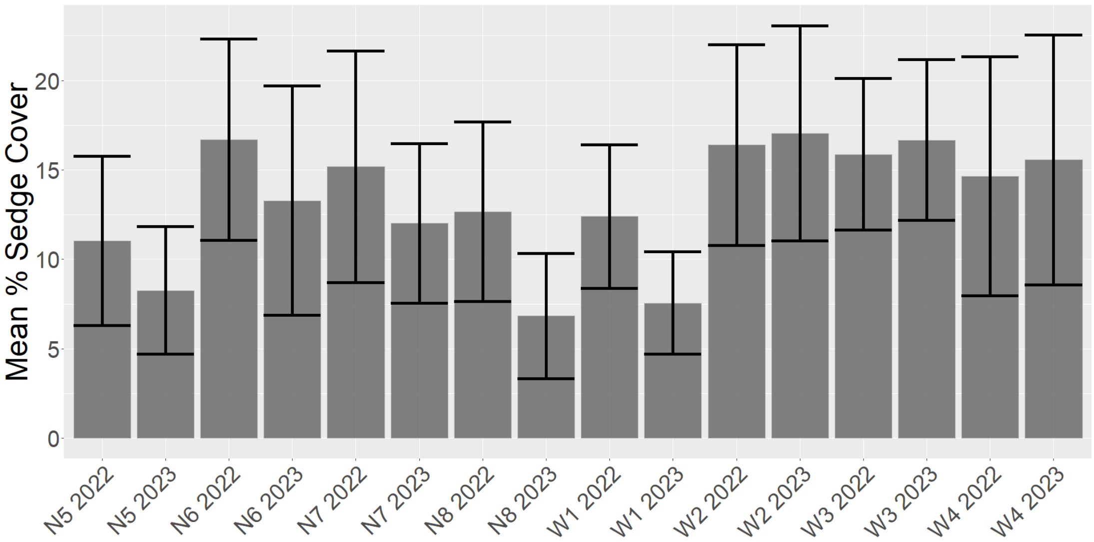


Figure 7. Bar graphs present the mean % cover of bare ground (A) and sedge species (B) of each field in 2022 and 2023 with error bars based on a 0.95 confidence interval.

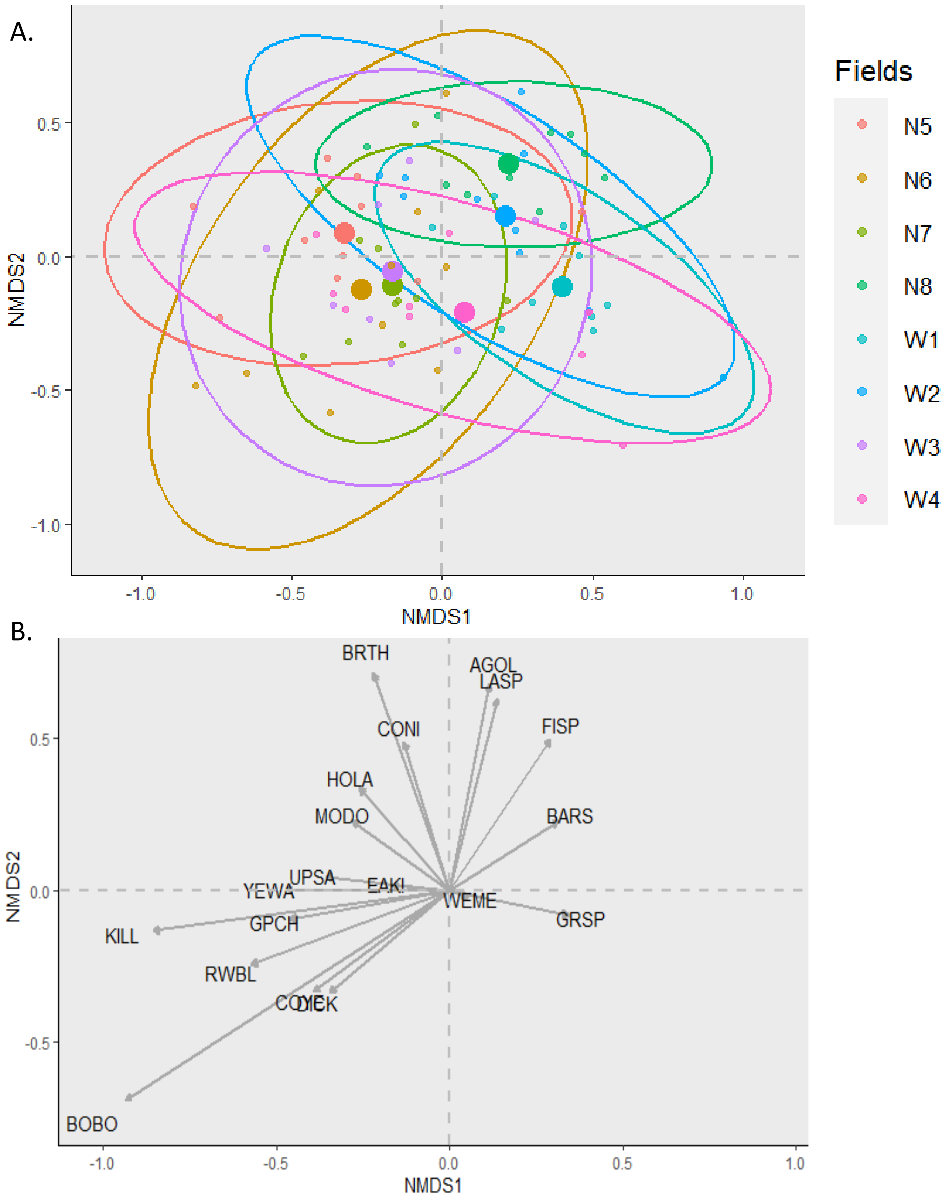


Figure 8. NMDS ordination plots of point count sites categories by Field (A) and avian species (B). Stress for this ordination was reported as 0.2125. Large centroids in A indicate the mean position in the ordination for corresponding fields. Ellipses show the distribution of sites inside within the corresponding Fields. Both ordinations are plotted on the same scale so that the location of sites in A can be compared to the avian species composition in ordination B. Sites are plotted so that those with similar avian communities are closer together (A). Arrows point in the direction representing an increase in abundance of the indicated species in that region (B). Bird abbreviations: AGOL(American Goldfinch, LASP (Lark Sparrow), FISP (Field Sparrow), BARS (Barn Swallow), GRSP (Grasshopper Sparrow), WEME (Western Meadowlark), BOBO (Bobolink), RWBL (Red-wing Blackbird), KILL (Killdeer), COYE (Common Yellowthroat), GPCH (Greater Prairie Chicken), YEWA (Yellow Warbler), EAKI (Eastern Kingbird), DICK (Dickcissel), UPSA (Upland Sandpiper), MODO (Mourning Dove), HOLA (Horned Lark), CONI (Common Nighthawk), BRTH (Brow Thrasher).

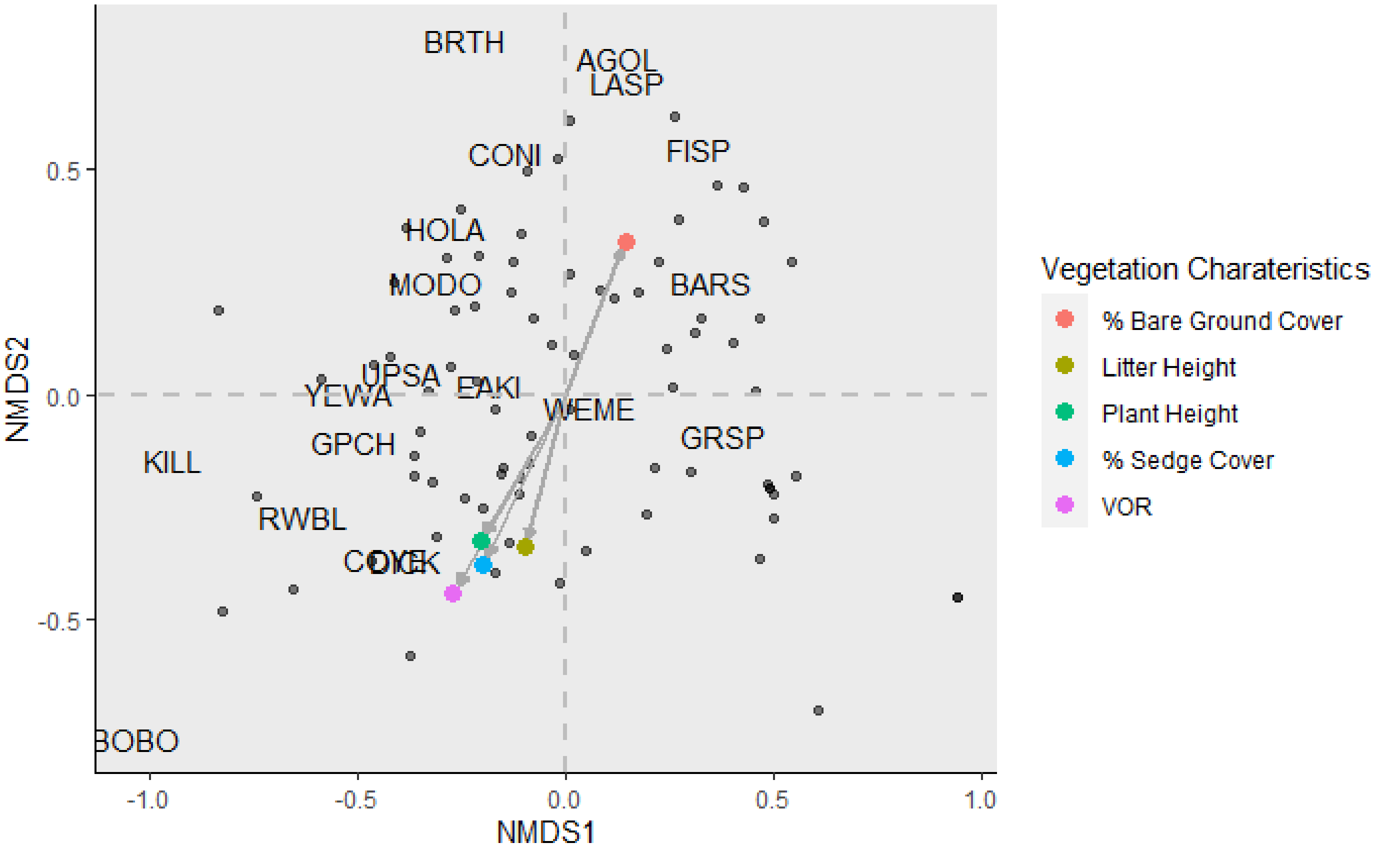


Figure 9. NMDS ordinations plot of point count sites and avian communities overlaid with the significant vegetation structure variables of interest. Stress for this ordination was reported as 0.2125. Arrows point in the direction of increases in the indicated vegetation measurement. This ordination is plotted at the same scale as those in Figure 8 and can be compared. Bird abbreviations: AGOL(American Goldfinch, LASP (Lark Sparrow), FISP (Field Sparrow), BARS (Barn Swallow), GRSP (Grasshopper Sparrow), WEME (Western Meadowlark), BOBO (Bobolink), RWBL (Red-wing Blackbird), KILL (Killdeer), COYE (Common Yellowthroat), GPCH (Greater Prairie Chicken), YEWA (Yellow Warbler), EAKI (Eastern Kingbird), DICK (Dickcissel), UPSA (Upland Sandpiper), MODO (Mourning Dove), HOLA (Horned Lark), CONI (Common Nighthawk), BRTH (Brow Thrasher).

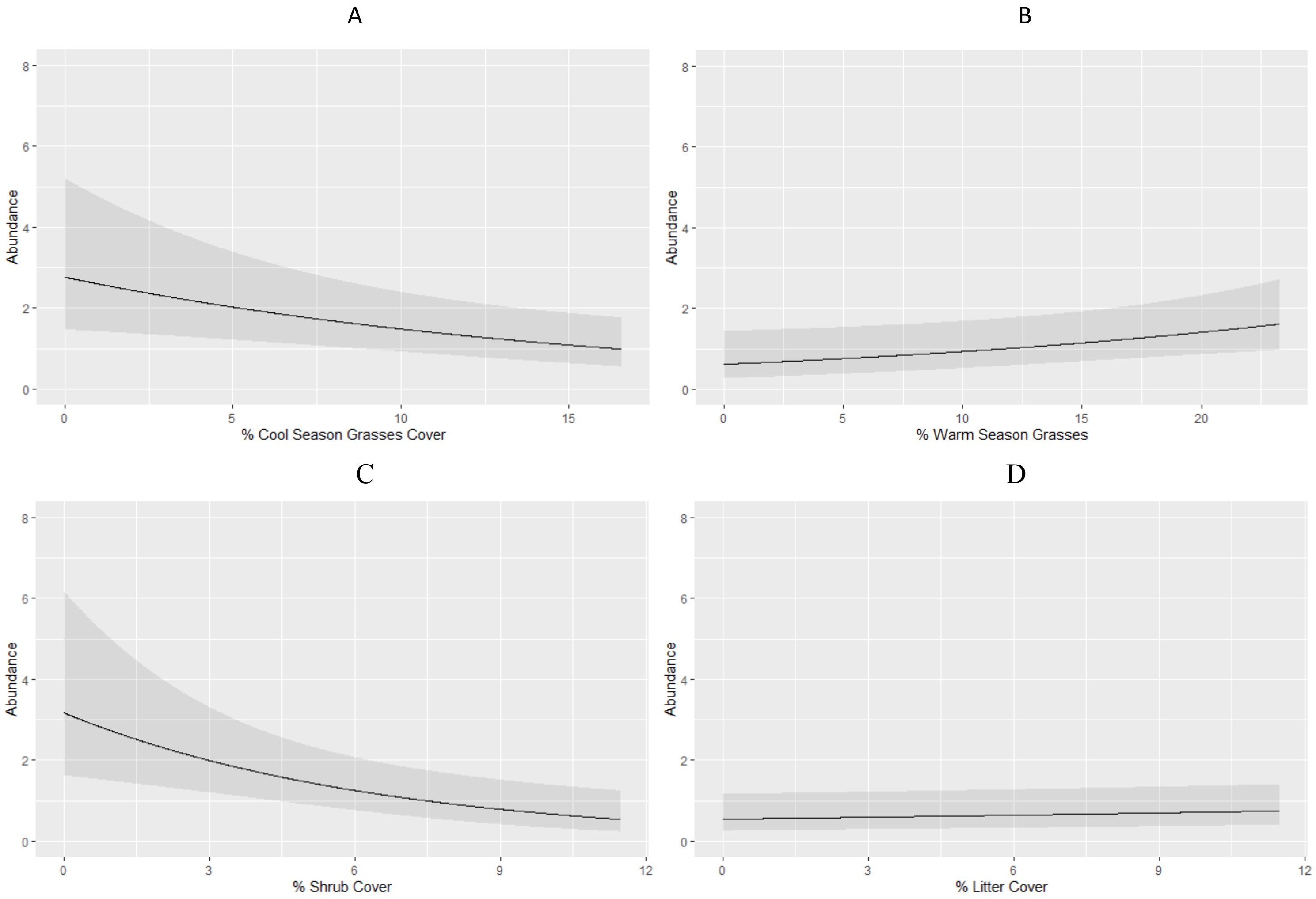


Figure 10. Response of Dickcissels to Cool Season Grass Cover (A), Warm Season Grass Cover (B), Shrub Cover (C), and Litter Cover (D). Shaded areas represent 85% confidence intervals.

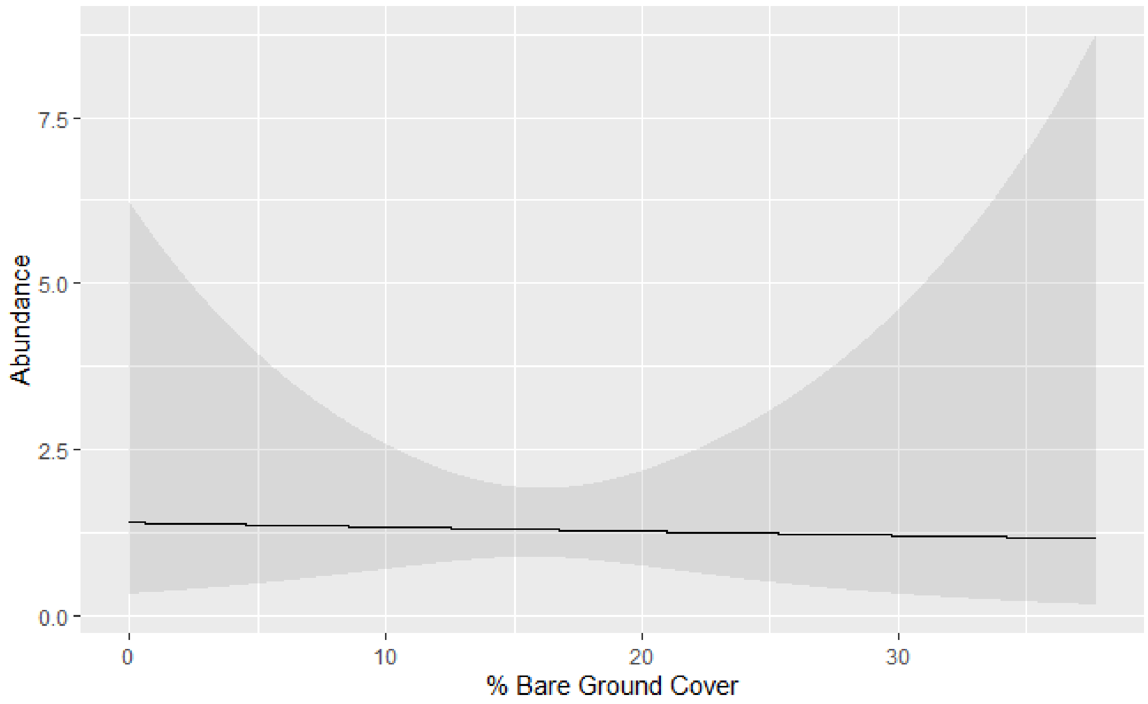


Figure 11. Response of Western Meadowlarks to Bare Ground Cover. Shaded area represents 85% confidence interval.

Chapter 6 – Conclusion

The Nebraska Sandhills are one of the most intact grassland systems in the world but since European colonization they have been increasingly managed for the middle, creating a large homogenous system where there was once a heterogenous, dynamic system. The homogeneity induced by moderate management practices has limited its ability to support a diversity of wildlife species and left it vulnerable to changes in its stable state. This is illustrated by the decline of grassland birds and the invasion of woody species such as Eastern Red Cedar in grasslands across North America. Patch-burn grazing has been introduced in other grassland systems as a way to restore historic fire-grazing interactions that once shaped the Great Plains and promote heterogeneity across the landscape. The Nebraska Sandhills have a long history of fire suppression and a cultural fear of fire and the destabilization of sand dunes that is often associated with it. Because of this, the effects of fire in the Sandhill are not well understood. The purpose of this research is to understand what ecological impacts a patch-burn grazing system will have in the Nebraska Sandhills.

One of the biggest impediments to the use of fire in the Nebraska Sandhills is the fear that the fire will destabilize the dunes by destroying the grasses that are holding them together and damaging the soil. The recent research into this subject though has shown that the Sandhills in their current state can recover from extreme fire situations. Chapter 1 of this thesis explores the issue of possible damage that the fire may have on the soil and a possible increase in soil movement in the period before the vegetation recovers. The results of the soil nutrient comparison showed that there was little difference between burned and unburned areas. The fast and less intense nature of a controlled grassland fire prevented any damage from occurring. They also showed that soil movement did not significantly increase following the fire. While the fire most certainly left the soil bare and more vulnerable. The movement that occurred was minimal and local, and soil was not being carried outside of the area. The accumulated mass of underground plant roots that holds the dunes together was able to weather the disturbance and keep the dunes stable until aboveground vegetation and cover returned.

One of the largest reasons for implementing a patch-burn grazing system lies in its ability to affect change in the structural composition of the vegetation and induce a more heterogeneous system. Many of the benefits of patch-burn grazing comes from its ability to do this. The one other time that patch-burn grazing was studied in the Nebraska Sandhills was in a non-traditional ranching setting that used American Bison as its grazers at low stocking rates and across wide areas. This research uses the system in a more traditional ranching setting with cattle and would be more applicable to average producers in the Sandhills. Chapter 2 addresses the patch-burn grazing system's ability to induce change in vegetation structure and increase heterogeneity. The results show that over the two years of this research the first field that was burned had a significantly different vegetation structure, mainly in the absence of standing dead plant material and litter that burned off in the fire and the increase of bare ground. The species community composition wasn't significantly affected by the disturbance other than a small increase in forbs following burns, but that is to be expected as significant changes in the community would begin to occur after several iterations of this treatment. The ability to detect an increase of the heterogeneity in the patch-burn grazing system at the management unit level was limited by the incomplete burn in the second year and the inability to capture more than the initial first two years of the system's cycle. The ability of patch-burn grazing to produce heterogeneity comes from its ability to shift different successional stages across the landscape through multiple years of treatment. The change in structure of the burned fields does create between-field structural heterogeneity and persistence in the change in vegetation structure exhibited by the first field to burn does support the idea that through a full cycle of patch-burn grazing, this treatment has the ability to increase heterogeneity in the Nebraska Sandhills larger scales.

Patch-burn grazing has been put forward as a management solution for improving the abundance and diversity of the declining guild of grassland bird species, through increasing their available habitat diversity. As with its ability to affect change in vegetation structure, it has been shown to have a positive effect in other grassland systems but has not been thoroughly studied in the Nebraska Sandhills. Chapter 3 addresses the impact that patch-burn grazing has on grassland bird communities in the Nebraska Sandhills. The results show differences in the communities of burned fields versus unburned fields, highlighting the system's ability to produce different habitat types to attract different communities of grassland birds. It also seems to have a positive and stabilizing effect on species diversity. In the face of a dry spring the diversity of the control systems drops significantly but the patch-burn grazing system was not nearly as affected. The ability to model certain species abundance was limited due to excess variability. Little support for the system having an effect was mostly on species abundance likely due to those species that were able to be modeled being some of the most abundant and well adapted to the vegetative state present in the study area before treatment.

The results of this research support the use of patch-burn grazing as a management tool in the Nebraska Sandhills. It was able to provoke the positive changes that were predicted through the use of the system while also proving to have limited trade-offs in connection to the health and stability of the soil. Managers and producers in a grassland setting face many challenges and uncertainties and need the tools to face them. Patch-burn grazing has been shown with this research to be an effective tool in the Nebraska Sandhills that can be used to meet those challenges.