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Patch-Burn Grazing (PBG) is a rangeland management strategy that promotes heterogeneity across a landscape by burning discrete patches of land. This is a contrast to Annual-Burn Grazing (ABG) which promotes homogeneity across the landscape and is commonly used across the rangelands of the midwestern United States. The heterogeneity generated by PBG has been shown to benefit a variety of taxa, including birds, small mammals, and plants. However, the impacts of PBG on invertebrate communities are not well understood. This thesis investigates the impacts of PBG on the invertebrate communities of Kansas rangelands. I compare aboveground and belowground invertebrate richness, evenness, and abundance in PBG plots to those in ABG plots, examining both mean shifts and changes in variance across the landscape. My results show that PBG changes mean aboveground invertebrate community composition and increases variance around that mean. However, aboveground invertebrate richness, evenness, and total abundance were not impacted by PBG. For belowground invertebrate communities, I only observed a significant difference in variance among plots based on years since burning. Together, my thesis results suggest that PBG may be a beneficial management strategy for conservation. Because PBG promotes heterogeneity across a landscape, benefiting many taxa and mostly not impacting invertebrates, it is a conservation strategy worth consideration.

IMPACTS OF PATCH BURN GRAZING ON THE INVERTEBRATE COMMUNITES OF KANSAS RANGELANDS

by

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CHAPTER I: THESIS INTRODUCTION

Heterogeneity plays a fundamental role in driving ecosystem diversity, particularly in grassland ecosystems (Hovick et al., 2015). Grasslands cover over a quarter of Earth's terrestrial surface, comprising 80% of agriculturally active land, and harbor remarkably high levels of biodiversity (Petermann & Buzhdygan, 2021; Boval & Dixon, 2012). However, conventional management practices, such as annual burning and grazing (ABG), often lead to landscape homogeneity, negatively impacting ecosystem health and function (Ricketts & Sandercock, 2016). To address this issue, patch burn grazing (PBG) has emerged as an alternative approach, promoting landscape heterogeneity by alternating grazing and discrete fires (Weir et al., 2013). PBG has shown positive effects on biodiversity, particularly for grassland birds and small mammals (Augustine & Derner, 2015; Derner et al., 2009; Ricketts & Sandercock, 2016). However, the impacts of PBG on other taxa, such as invertebrates, remains largely unexplored.

Invertebrates are often overlooked members of ecosystems. Yet they contribute vital ecosystem functions, including seed translocation, pollination, and nutrient cycling (Elizalde et al., 2020; Blouin et al., 2013). Given the significant role of invertebrates in grasslands, understanding the effects of rangeland management strategies on invertebrate communities is crucial for informing conservation and management practices. In my thesis, I investigate the consequences of PBG on invertebrate abundances and community composition in a tallgrass prairie ecosystem, addressing two primary questions: (1) Do invertebrate abundance and community composition differ across PBG compared to ABG in both mean and/or variance? (2) How does invertebrate community composition change over time at the individual watershed level in response to different fire-grazing regimes.

Answering these questions will provide valuable insight into the impacts of PBG on invertebrate communities. The results of this study can inform rangeland managers of the impacts of a relatively new land management technique on invertebrate communities in the mesic grasslands of the North American Great Plains, ultimately helping land managers make more informed decisions that allow them to balance both conservation and productivity goals. Additionally, because grasslands are incredibly diverse and are easily accessible in many parts of the world, they serve a fantastic model ecosystem to explore how heterogeneous ecosystems can impact invertebrate communities more broadly. The results of this work can be compared to the impacts of heterogeneity on invertebrate communities in ecosystems around the world to help increase the overall understanding of the role of variation across the landscape.

CHAPTER II: UNDERSTANDING THE EFFECTS OF ALTERNATIVE FIRE-GRAZING MANAGEMENT ON ABOVEGROUND GRASSLAND INVERTEBRATE BIODIVERSITY

Introduction

Heterogeneity, broadly speaking, is a term used to describe variability within a group. In the context of ecosystems, the concept can be applied to spatial variability across a landscape, such as patchiness of vegetation. The "habitat heterogeneity hypothesis" suggests that increased structural variability supports increased biodiversity within an ecosystem (Tews et al. 2004, Staudacher et al. 2018). Numerous publications have found support for this hypothesis, observing a positive relationship between increased habitat variability and biodiversity (Tews et al. 2004, Hovick et al. 2015), including arthropods (Tews et al. 2004).Therefore, in many ecosystems, it may be advantageous to promote heterogeneity across the landscape in order to promote biodiversity and ecosystem function. However, more research is needed to understand exactly when, where, and how heterogeneity is advantageous.

Grasslands cover more than a quarter of the Earth's terrestrial surface, supporting 80% of the world's agriculturally active land (Boval and Dixon 2012). Additionally, grassland ecosystems have one of the highest levels of biodiversity per area of any ecosystem type (Petermann and Buzhdygan 2021). In addition to their ecological value, grasslands are also agriculturally important for the production of domestic livestock, such as cattle. Rangelands provide a critical animal food source, providing about 70% of the required feed for the world's domestic ruminants (Lund 2007). However, the management practices often used to maintain livestock in rangeland systems can damage the ecosystem and reduce the habitat quality for coexisting natural species (Toombs and Roberts 2009).

Grasslands are naturally heterogeneous systems. The promotion of landscape heterogeneity within rangeland ecosystems has been suggested as a mechanism to protect wildlife and meet conservation goals (Toombs and Roberts 2009). Increased heterogeneity may be beneficial for ecosystem health because a variety of vegetative structures across the landscape provides habitat for a wider variety of animals, such as birds (Fuhlendorf et al. 2006). However, the impacts of vegetative heterogeneity have not been explored with regards to their impacts on grassland invertebrate communities. It is plausible that by promoting vegetation heterogeneity in grassland ecosystems, the invertebrate community will experience increased biodiversity as a result of heightened habitat and plant resource opportunities.

Currently, standard practice in mesic rangelands, such as the tallgrass prairie ecoregion of the United States, is to burn the entirety of a managed pasture every year in a practice known as annual burning and grazing (ABG) (Ricketts and Sandercock 2016). ABG management promotes homogeneity across the landscape, with negative consequences for ecosystem biodiversity (Ricketts and Sandercock 2016). Recently, patch burn grazing (PBG) has emerged as an alternative to ABG. In a PBG management style, a grazed area is burned in alternating patches. Because cattle prefer to graze recently burned areas, discrete fires will naturally create discrete grazing with no need for a land manager to direct animals (Weir et al. 2013). A positive consequence of discrete grazing is that vegetation is grazed in a non-uniform manner, leading to differences in vegetation across the landscape (Weir et al. 2013). This means that the pasture is overall more heterogenous, a positive result for ecosystem health and function (Ricketts and Sandercock 2016). The use of spatially and temporally discrete fires to alter ungulate grazing patterns in PBG management thus promotes a “shifting mosaic” of habitat for wildlife across the landscape (Fuhlendorf et al. 2006). Increased landscape heterogeneity in PBG systems has been shown to positively impact grassland bird and small mammal biodiversity (Derner et al. 2009, Augustine and Derner 2015, Ricketts and Sandercock 2016). In addition to aiding conservation goals, PBG provides similar levels of cattle production (Fuhlendorf and Engle 2004), thus promoting benefits for both nature and people. However, the impacts of PBG on taxa other than birds and small mammals remain unknown. In particular, an exploration of the impacts of PBG on the invertebrate community would provide valuable insight into the overarching impacts of this management style.

Invertebrates are a vital part of many ecosystems. While the functional roles of invertebrates are vast and likely not fully understood, a few are immediately eye catching. Insects provide important services such as seed translocation, pollination, and pest management (Elizalde et al. 2020). Additionally, invertebrates can fundamentally transform the structure of the ecosystem around them, including alterations to the soil structure, nutrient cycle, and water drainage (Blouin et al. 2013). These roles are incredibly significant, and likely only provide a small snapshot of the scope and scale of the impacts that invertebrates have on ecosystem function, particularly in rangeland ecosystems. Thus, an improved understanding of the effects of proposed rangeland management strategies on invertebrate communities is necessary before large-scale implementation.

Here, I investigate the consequences of PBG on invertebrate abundances and community composition in a tallgrass prairie ecosystem. I specifically address three major questions: (1) Does mean invertebrate abundance or community composition differ across PBG compared to ABG? Recalling that discrete fires promote vegetation heterogeneity and therefore a diversity of habitats, I hypothesize that PBG will result in increased abundances and biodiversity of invertebrate communities because of the changes in the underlying vegetative structure. (2) Does variance in invertebrate abundance or community composition differ across PBG when compared to ABG? Because the vegetation is more variable in PBG than ABG as a result of fire-grazing patches, I hypothesize that the supported invertebrate communities will be different in composition, with higher variability across the landscape. Finally, (3) How does invertebrate community composition change with respect to years since burning? I hypothesize that invertebrate composition will vary at the individual watershed level in correspondence with the years since burn due to increasing forb cover and decreasing nutrient availability with time since burning. The results of this work will provide valuable insight into the impacts of PBG and will help land managers make more informed decisions regarding optimal environmental and economical land management practices.

Methods

Study Site**:** My study took place at the Konza Prairie Biological Station (KPBS) located in Manhattan, Kansas. KPBS is a ~8,600 acres native tallgrass prairie ecosystem and my study site within KPBS is dominated by *Andropogon gerardii, Sorghastrum nutans, Dalea multiflora, Rhus glabra*, and *Amorpha canescens* (Blair 2024). The climate is typified by warm, wet summers and dry, cold winters. The climate is a warm, mesic system, with annual rainfall averaging 803 mm (Nippert 2024) and average daily maximum temperature is 19.5 °C, average daily minimum temperature is 6.2 °C and the mean daily temperature is 12.8 °C.

Study Design**:** Within the boundaries of KPBS, I collected data within units where either an ABG or PBG strategy (N=2 each) has been employed since 2010. Two watersheds (93 ha, 76 ha) were under ABG management and burned in the spring each year. Each of the two PBG units (455 ha, 219 ha) were split into three watersheds, with the watersheds in a rotation of tri-annual spring burning, such that in any given year there was one watershed that had been burned that year, one burned the year previous (1 year since burning), or and one burned two years previous (2 years since burning). Sampling was repeated across the course of three years, spanning from 2021-2023.

***Sampling*:** Four sampling transects are dispersed throughout each watershed of the ABG and PBG units. I established 1 x 1 m plots located at approximately 16 m and 38 m along each transect within which aboveground invertebrate samples were collected, resulting in eight plots per watershed in each year for a total of 64 plots across all grazing units (N=16 in ABG; N=48 in PBG). A reverse leaf blower was used to extract invertebrates from the 1 m^2 quadrant over the duration of 60 seconds. All collection took place during the regional peak growing season (early July) and was conducted from approximately 11 am to 2 pm during sunny, relatively still days. Extracted invertebrates were then placed in zip-sealed bags in the field and stored in a cooler, after which they were brought to the lab and frozen within 2 hours of collection. Any invertebrates in the families Acrididae (grasshoppers) or Tettigoniidae (katydids) that were noted to exit the plot as the blower approached were counted and recorded as "observed." Samples were identified to taxonomic family by their visual characteristics and counted.

***Statistical Analysis*:** All analyses were conducted in R (version 4.3.2)(R Core Team 2023). To examine the effects of management on mean and dispersion difference in invertebrate community composition, I conducted two permutational multivariate analysis of variance (PERMANOVA; mean community difference) and PERMUTEST (difference in dispersion) for each year of data using the 'vegan' package (Oksanen et al. 2022). First, I assessed the multivariate composition of family abundance data between ABG and PBG management areas, with PBG subset to 16 random plots to account for the unbalanced design. I set management treatment as a fixed effect and Bray-Curtis dissimilarity index as the distance metric. Second, I assessed the effect of years since burning for watersheds in the PBG management areas compared to the annually burned ABG watersheds. For the years since burned analysis, I did not subset the data because the sampling design across the watersheds is balanced.

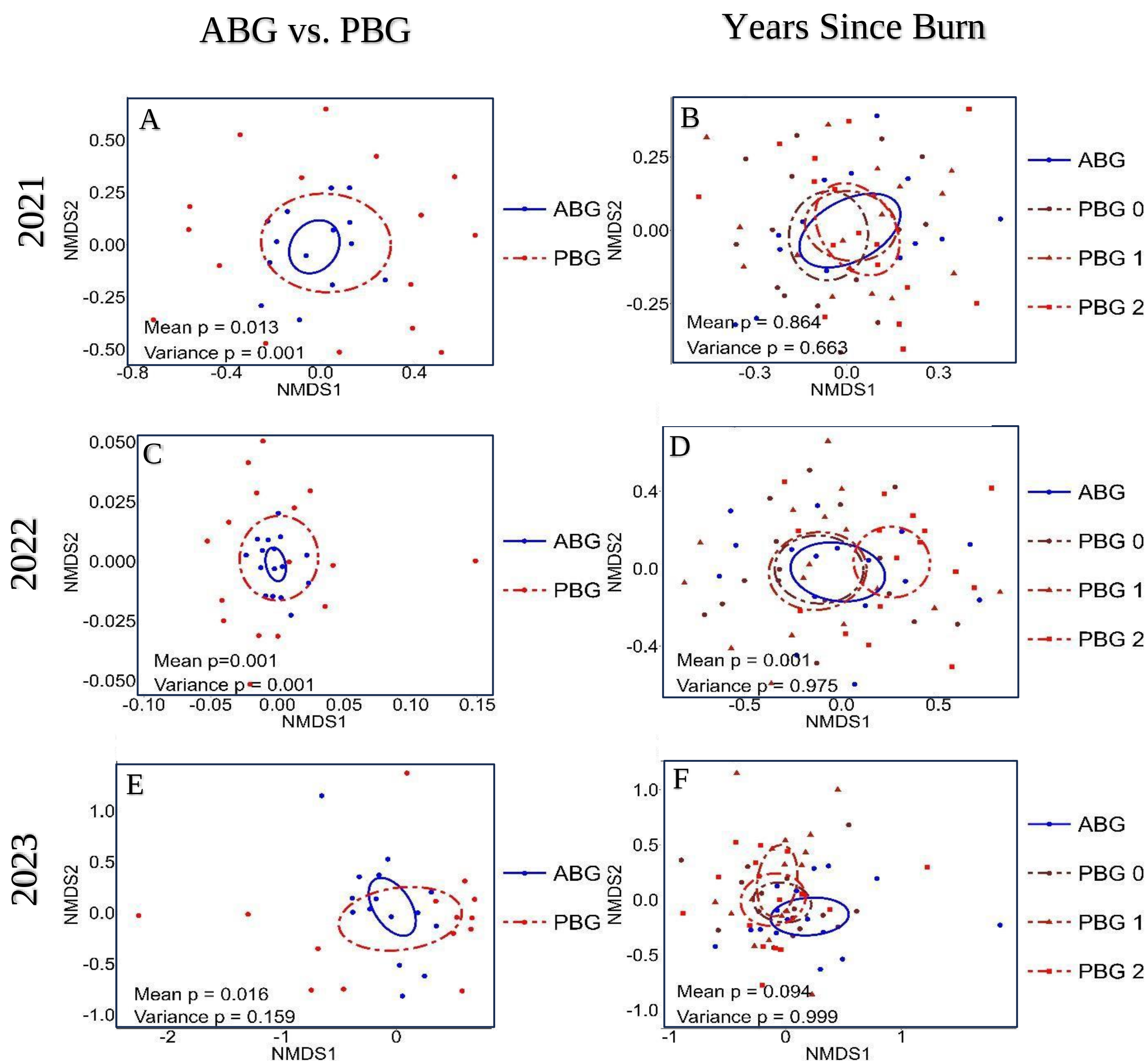
To examine univariate community metrics (richness and evenness) and abundance data, I utilized bootstrapping to account for the uneven sampling effort across ABG vs PBG management areas. For each year of data, I used the ‘boot’ package (Canty et al. 2024) to subsample 16 of the PBG plots for a comparable sample size with ABG plots, repeating the subsampling 1000 times to develop a distribution of PBG invertebrate richness, evenness, and abundance. I then utilized z-score calculations to compare the PBG distributions to the mean ABG value for richness, evenness, and abundance. As above, for the years since burned analysis, I did not utilize bootstrapping because the sampling design across the watersheds is balanced.

Additionally, using my bootstrapped dataset for PBG and non-bootstrapped dataset for ABG, I calculated the coefficient of variation for ABG and PBG richness, evenness, and abundance. I then utilized z-score calculations to compare the PBG distributions to the mean ABG value for the coefficient of variation for richness, evenness, and abundance.

Results

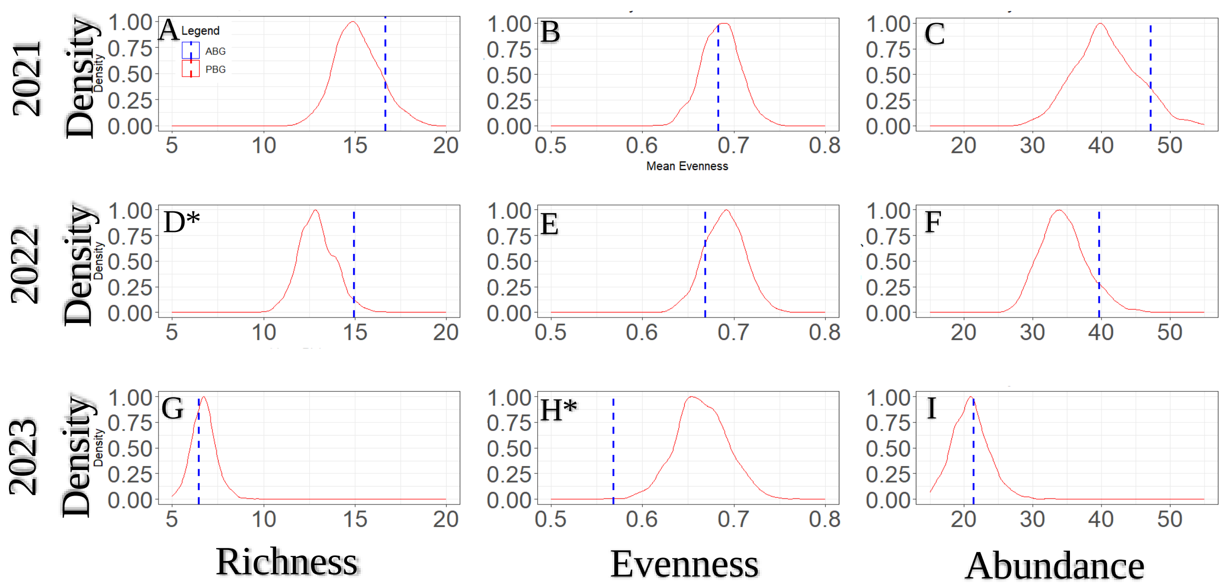
Community Composition

Figure 1: NMDS Comparing Invertebrate Communities Between ABG vs PBG and Years Since Burned.



Note. NMDS demonstrating shifts in mean and variance in aboveground invertebrate community composition across (B, D, F) ABG vs PBG treatments during the three years of monitoring or (A, C, E) by years since burning. Points represent the community composition within each plot, with ellipses representing 95% confidence intervals around mean composition for each treatment. Mean composition significantly differs between all ABG vs PBG treatments (A, C, E) and compositional variance differences in 2021 (A) and 2021 (C) but 2023 (E). For years since burn, mean composition only differed in 2021 (D) between treatments. Compositional variance did not differ across any treatments (B, D, F).

Figure 2: Density Plots Comparing Aboveground Invertebrate Richness, Evenness and Abundance.



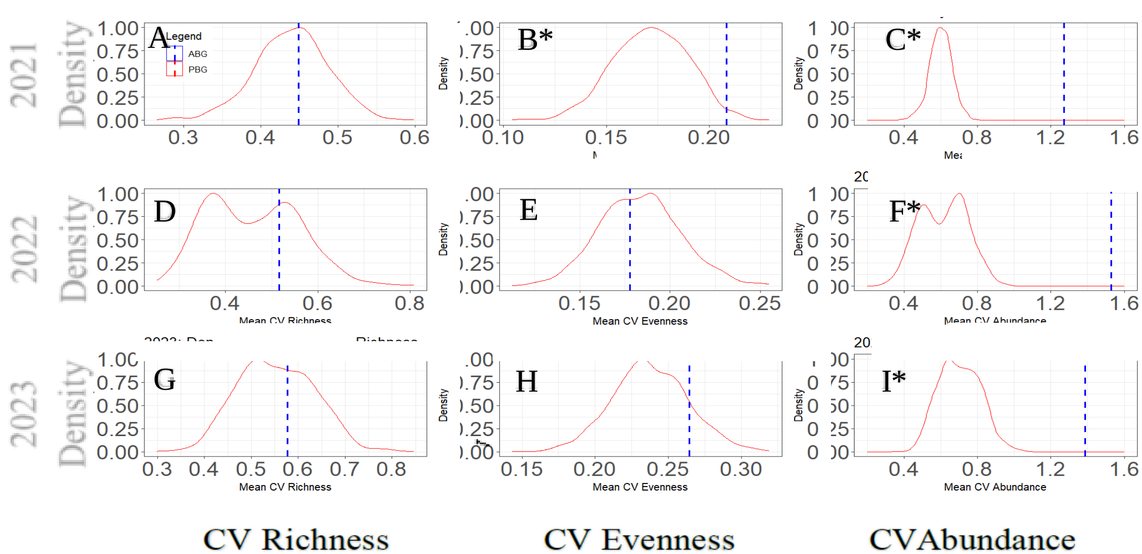
Note. Density plots comparing mean richness (A, D, G), evenness (B, E, H), and total abundance (C, F, I) of aboveground invertebrates between ABG (blue dashed lines) and PBG (red curves) across three years of data collection (A-C: 2021; D-F: 2022; G-I: 2023). Significant differences were assessed at $p<0.05$. For most panels (A, B, C, E, F, G, I), I did not see differences between treatments. However, I did see differences towards ABG in 2022 richness (D) and a difference towards PBG in 2023 evenness (H).

ABG vs PBG Treatment: I found statistically significant differences in mean aboveground community composition between the ABG and PBG treatments for 2021 ($F_{1,28}=1.96$ $p=0.013$; Figure 1A), 2022 ($F_{1,30}=4.52$, $p=0.001$; Figure 1C), and 2023 ($F_{1,30}= 2.34$, $p=0.016$; Figure 1E), as well as dispersion among plots for 2021 ($F_{1,30}= 23.434$, $p=0.001$;

Figure 1A) and 2022 (F1,30=59.9, p=0.001; Figure 1C). However, I did not see a statistically significant difference in compositional variance in 2023 (F1.30= 2.05, p=0.159; Figure 1E). Mean aboveground invertebrate richness was significantly higher in ABG compared to PBG in 2022 (z = 2.03, p = 0.043; Figure 2D), but not 2021 (z = 1.24, p = 0.217; Figure 2A) or 2023 (z = 0.45, p = 0.657; Figure 2G). For evenness, I found no significant differences between treatments for 2021 (z = 0.15, p = 0.885; Figure 2B) and 2022 (z = 0.95, p = 0.343; Figure 2E). However, I did see a significant difference across treatments for mean evenness in 2023, with PBG evenness being significantly higher than ABG evenness (z = 3.40, p = 0.001; Figure 2H).

Coefficient of Variance (CV): I compared ABG vs PBG coefficients of variation for richness, evenness, and abundance. I saw no significant difference for CV richness 2021 (z-score = 0.19, p = 0.847; Figure 3A), 2022 (z-score = 0.56, p = 0.574; Figure 3D) or 2023 (z-score = 0.30, p = 0.768; Figure 3G). For CV evenness, I did see a significant difference in 2021 with ABG being greater than PBG (z-score = 2.02, p = 0.040; Figure 3B). There was not significant difference for CV evenness in 2022 (z-score = -0.25, p = 0.802; Figure 3E) and 2023 (z-score = 1.03, p = 0.303; Figure 3H).

Figure 3: Density Plots Comparing Mean CV Richness, Evenness and Abundance.



Note. Density plots comparing mean CV richness (A, D, G), evenness (B, E, H), and CV abundance (C, F, I) of aboveground invertebrates between ABG (blue dashed lines) and PBG (red curves) across three years of data collection (A-C: 2021; D-F: 2022; G-I: 2023). Significant differences were assessed at $p<0.05$. For most panels (A, D, E, G, H) we did not see a significant differences between treatments. However, I did see differences towards ABG in 2021 CV evenness (B) and 2021-2023 CV Abundance (C, F, I).

***Years Since Burn*:** I found a statistically significant difference ($F_{3,60}$=2.11, p=0.001; Figure 1D) in the 2022 aboveground community composition among different years since burn with PBG after two years since having a difference. There were no significant differences for 2021 ($F_{3,60}$ = 1.01, p=0.864; Figure 1B) or 2023 ($F_{3,60}$ =1.38, p=0.078; Figure 1F). No significant difference was observed in multivariate dispersion among the among different years since burn for 2021 ($F_{3,57}$=0.52, p=0.663; Figure 1B), 2022 ($F_{3,60}$=0.08, p=0.975; Figure 1D), or 2023 ($F_{3,60}$= >0.01, p=0.999; Figure 1F). Additionally, no statistically significant difference was observed for richness across years since burn in 2021 ($F_{3,56}$ = 0.44, p = 0.725; Figure 4A) or 2022 ($F_{3,59}$ = 2.58, p = 0.062; Figure 4D). I did observe a significant difference in mean richness among years since burning in 2023, with the PBG watershed that was burned one year previous having greater aboveground invertebrate richness than the PBG watershed burned in the year of sampling or two years prior ($F_{3,58}$ = 4.38, p = 0.008; Figure 4G). No statistically significant difference was observed for mean evenness across years since burn for 2021 ($F_{3,56}$ = 2.26, p = 0.091; Figure 4B), 2022 ($F_{3,59}$ = 0.90, p = 0.446; Figure 4E), or 2023 ($F_{3,58}$ = 2.46, p = 0.072; Figure 4H)

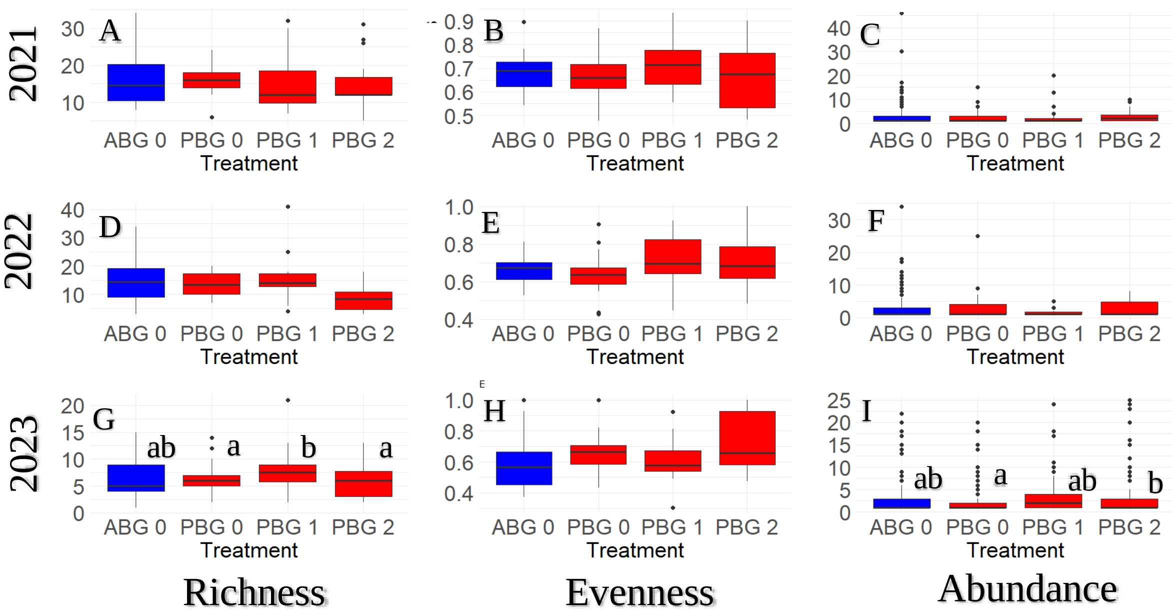
Abundance

***ABG vs. PBG*:** For ABG vs PBG abundance, I found no significant differences for abundance for 2021 (z = 1.15, p = 0.252; Figure 2C), 2022 (z = 1.51, p = 0.130; Figure 2F), or

2023 (z = 0.14, p = 0.886; Figure 2I). I did see significant differences for CV Abundance with ABG being greater in 2021 (z-score = 10.93, p = <0.001; Figure 3C), 2022 (z-score = 7.04, p = <0.001; Figure 3F) and 2023 (z-score = 6.09, p = <0.001; Figure 3I).

Years Since Burn: There was no significant difference in aboveground invertebrate abundance by years since burning in 2021 ($F_{3,56}$ = 0.26, p = 0.857; Figure 4C) or 2022 ($F_{3,59}$ = 0.71, p = 0.553; Figure 4F). However, in pairwise comparison, I did see a significant difference in 2023 with PBG burned two years previously being higher in richness than PBG burned in the same year I collected ($F_{3,59}$ = 2.98, p = 0.039; Figure 4I).

Figure 4: The Effects of Years Since Burning in PBG and ABG on Abundance, Richness, and Evenness on Aboveground Invertebrates.



Note. The effect of years since burning in PBG (red) and ABG (blue) on (C, F, I) abundance, (A, D, G) richness, and (B, E, H) evenness of aboveground invertebrate herbivores across three years of sampling (A-C: 2021, D-F: 2022, G-I: 2023). Letters indicate significant differences between treatments. For most panels (A, B, C,D, E, F, H) I not did observe aa significant differences across years since burned treatments. However, in pairwise comparison, I did see significant differences amongst years since burned treatments for 2023 richness (G) and 2023 abundance (I).

Discussion

Overall, my results provide only partial support for the hypothesis that increased landscape heterogeneity with PBG would result in increased invertebrate biodiversity and abundance. With the exception of 2023 evenness, no metric of biodiversity was significantly higher in PBG. Additionally, ABG richness in 2022 is significantly higher than that of PBG, further failing to provide support for my hypothesis. However, I do see heightened variability in the community composition in PBG, which supports my hypothesis that landscape heterogeneity in burning should increase landscape heterogeneity in biotic communities.

The invertebrate response to fire generally appears to be variable (González et al. 2022). Differences in response may depend on how closely a given taxa associates with vegetation structure and/or their ability to readily recolonize a burned area (González et al. 2022). Burning frequency is known to have an effect on overall arthropod community composition, as increased fire frequency favors some orders while negatively affecting others (Kral et al. 2016). In context of my findings, this assertion is supported. The more frequent burn treatment (ABG) had a different aboveground invertebrate community composition on average when compared to my less frequent burn treatment (PBG). Furthermore, the variability of this composition was different for two of my three study years, likely driven by variability in years since burn across the PBG landscape. Overall, my findings support the concept that fire drives changes in invertebrate community composition.

I observed a non-significant trend towards increased mean species richness for ABG in 2021 and 2022, but not 2023 (drought year). Because my data showed community composition differences between these burn treatments, a possible driver of this trend could be differences in the ideal environmental conditions of the species that make up the two respective communities. Notably, I see no trend in 2023, which was a particularly dry year. This may be a suggestion that ABG has slight favorability in overall mean species richness for aboveground invertebrates, but only under certain favorable conditions.

My study was able to capture three years of abundance data. However, only one year of my abundance was obtained during a drought year. Under drought conditions, a decrease in plant biomass can often be expected, which in some ecosystems can result in declines in some invertebrate taxa (Barnett and Facey 2016). With this background in mind, it is clear that drought resistant management styles are needed to meet conservation goals. While I am limited on my PBG invertebrate data in the context of drought, I do see evenness having a resistance in PBG when contrasted with ABG.

The variance of invertebrate composition was greater in PBG when contrasted with ABG. This is in line with what was expected based on my original hypothesis. Heterogeneity in the vegetative structure is able to be achieved through the discrete burning management practice of PBG. This heightened heterogeneity has been shown to increase variability in other taxa, such as birds (Fuhlendorf et al. 2006). Therefore, the increased invertebrate compositional variability appears to be linked the complexity of the vegetative structure, just as bird communities are. This is a very interesting finding, as it supports the fundamental understanding of the link between vegetative structure and ecological communities.

For the coefficient of variation (CV), the lack of the statistically significant differences for richness and evenness are not surprising in the context of my previous results. However, increased CV for ABG in abundance across all three years is a surprising result, contrary to our hypothesis that variance across samples (*i.e.*, heterogeneity) would be lower in ABG than PBG. While it is not clear what factors drove this result, this is an interesting pattern and highlights the need for more research in order to elucidate the driver of this phenomenon.

The lack of strong, consistent differences between burn treatments across all years highlights the complexity of fire's effects on invertebrates. This aligns with other studies suggesting variable invertebrate responses depending on factors like fire severity, time since fire, and specific taxa involved (Kral et al. 2016, González et al. 2022). Further research with more years of data, incorporating factors like fire severity and specific invertebrate groups, could provide a clearer picture of how fire and grazing influence invertebrate communities over time. Additionally, consideration should be given to environmental variables that add further complexity.

Understanding the dynamics of aboveground invertebrate communities is crucial for ecosystem management and conservation efforts. Overall, PBG appears to be a useful management technique for the purpose of promoting heterogeneity and therefore potentially promoting select conservation goals. My results further confirm the view in the literature that habitat heterogeneity promotes increased variability in ecological communities. These findings are multifaceted in their impact with implications for both the underlying ecological theory as well as for land managers. There is now a deeper understanding of the impact of heterogeneity on invertebrate communities and therefore this can be utilized in management decisions.

CHAPTER III: UNDERSTANDING THE EFFECTS OF ALTERNATIVE FIRE-GRAZING MANAGEMENT ON BELOWGROUND GRASSLAND INVERTEBRATE BIODIVERSITY

Introduction

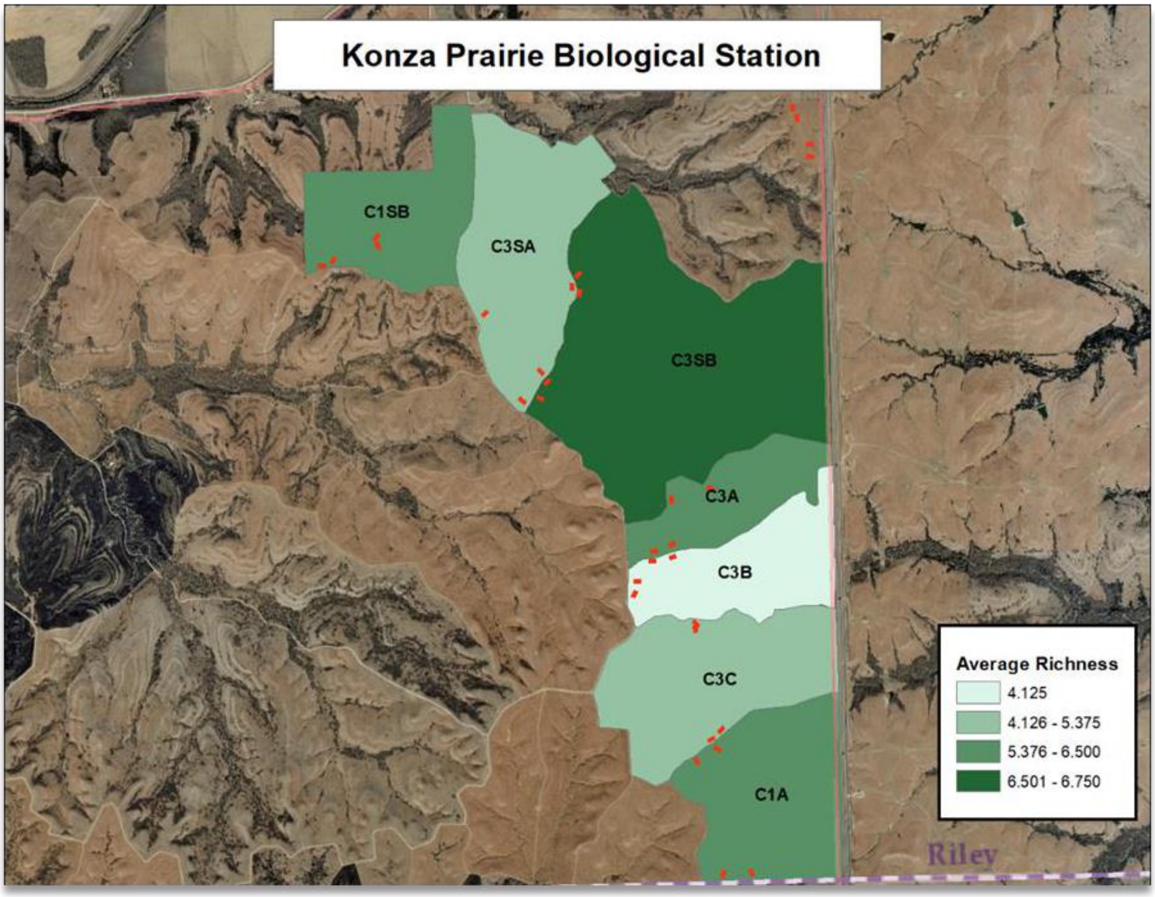
Soil invertebrates play a crucial role in numerous ecosystems, contributing significantly to their functioning and stability. They are recognized as valuable indicators of ecosystem health due to their sensitivity to environmental changes (Cifuentes-Croquevielle et al. 2020). Notably, the diversity of plants within an ecosystem has been found to directly influence the composition and abundance of belowground invertebrate communities (Eisenhauer et al. 2013)). Moreover, the presence and activity of soil fauna, including belowground invertebrates, have been shown to enhance the rates of litter decomposition (Zan et al. 2022). This process is vital for nutrient cycling and soil formation, highlighting the essential role of soil invertebrates in ecosystem processes. Given their ecological significance and their capacity to serve as bioindicators, assessing the belowground invertebrate community is critical when evaluating the overall health and functioning of an ecosystem. By monitoring changes in their populations and diversity, scientists can gain valuable insights into the state of the environment and the potential impacts of human activities or management strategies. Thus, understanding and conserving belowground invertebrate communities are essential for maintaining ecosystem resilience and sustainability.

I specifically address three major questions: (1) Does mean belowground invertebrate abundance and community composition differ across PBG compared to ABG? Because discrete fire impacts vegetation, and it is believed that there is link between vegetation and soil invertebrates, it is reasonable to conclude that mean composition would likely differ between PBG and ABG. I expect to see an increase in PBG belowground invertebrate abundance due to increased habitat and food opportunities created by the more complex vegetation structure. (2) Does variance in belowground invertebrate abundance and community composition differ across PBG compared to ABG? PBG is known to promote a more complex and variable vegetative structure. Therefore, I believe that there will likely be a response observed in belowground invertebrates. Specifically, I expect variance to be higher in PBG when contrasted with ABG due the belowground invertebrate's likely connection to the vegetative structure. Finally, (3) does belowground invertebrate community composition change with regards to years since burning? I expect that as the plant community experiences a recovery time, it's composition will change. Because the plant community is changing, I expect there to be a downstream impact on the belowground invertebrate community. Therefore, years since burned should have an impact on the belowground community composition. The outcomes of this research will offer valuable understanding into the effects of PBG, aiding land managers in making well-informed choices concerning optimal environmental and economic land management strategies.

Methods

***Study Design*:** At Konza Prairie Biological Station (KPBS), my data collection focused on units where either annual burning and grazing (ABG) or patch burn grazing (PBG) strategies (N=2 each) have been in practice since 2010, as described in Chapter 1 (Figure 5). These watersheds followed a rotation schedule for spring burning conducted tri-annually, ensuring that in any given year, one watershed had been burned that year, another had experienced burning the previous year (1 year since burning), and the third had encountered burning two years prior.

Figure 5: Sampling Design for Belowground Invertebrate Assessment



Note. Sampling Design for Belowground Invertebrate Assessment. There are 7 total watersheds. All watersheds that contain the number 3 are PBG watersheds and all that contain the number 1 are ABG watersheds. Within each watershed, there are four transect. Red rectangle = transects. Filled polygons = Watersheds.

Sampling**:** In each watershed, four 50-m transects were established, spaced haphazardly across the upland areas. Plots were established at 16 m and 38 m along each transect, resulting in eight plots per watershed for a total of 64 plots across all grazing units (N=16 in ABG; N=48 in PBG). At each point, a 30 x 30 x 30 cm block of soil was targeted for removal (0.027 m^3). In some cases, soil blocks were less than the target depth of 30 cm due to the presence of rocks or very hard soil. Once each block of soil (one solid chunk) was removed from each plot, it was broken down by hand and any invertebrates visible to the naked eye were removed and immediately suspended in a 99:1 solution of 140 proof ethanol and glycerol for preservation. All belowground invertebrate collection took place from October 18 to 22, 2021. Samples were returned to the lab, where they were identified to taxonomic order and morphospecies. Each plot's samples were then air dried for approximately one hour at room temperature and weighed. Unfortunately, C3SC samples were lost in shipping, which resulted in one PBG watershed being excluded.

Statistical Analysis**:** All analyses were conducted in R (version 4.3.2). To examine the effects of management on invertebrate community composition, I conducted two permutational multivariate analysis of variance (PERMANOVA) using the 'vegan' package (Oksanen et al. 2022). First, I assessed the multivariate composition of morphospecies abundance data between ABG and PBG management areas, with management treatment as a fixed effect and Bray-Curtis dissimilarity index as the distance metric. Additionally, I assessed differences in community dispersion among plots within each management area using the 'vegan' package (Oksanen et al. 2022). These models were repeated, incorporating the year since burn for watersheds in the PBG management areas.

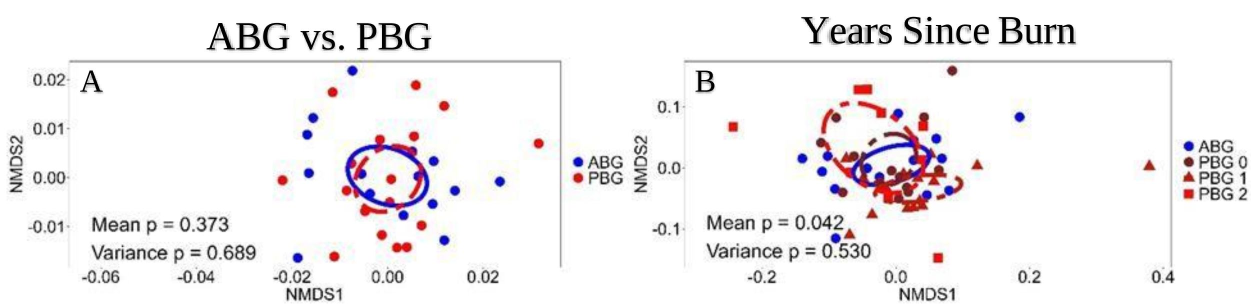
To examine univariate community metrics (richness and evenness) and abundance data, I utilized bootstrapping to account for the uneven sampling effort across ABG vs PBG management areas. Using the 'boot' package (Canty et al. 2024), I subsampled 16 of the PBG plots for a comparable sample size with ABG plots, repeating the subsampling 1000 times to develop a distribution of PBG invertebrate richness, evenness, and abundance. I then utilized z-score calculations to compare the PBG distributions to the mean ABG value for richness, evenness, and abundance.

Results

Community Composition & Abundance

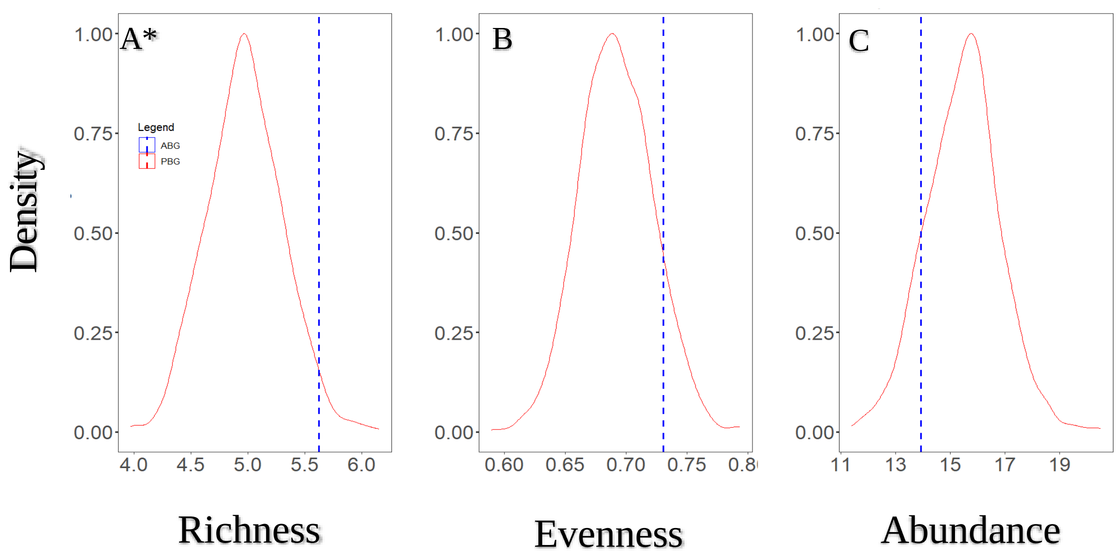
***ABG vs PBG Treatment*:** No significant difference was observed in belowground mean community composition between the ABG and PBG treatments ($F_{1,31}$ = 1. 1.02, p = 0.373; Figure 6A), or compositional variance among plots within each treatment ($F_{1,30}$ = 0.13, p = 0.689; Figure 6A). Morphospecies richness was significantly higher in ABG than PBG (z-score = 1.95, p = 0.0255; Figure 7A), however no significant differences were observed for evenness (z-score = 1.28, p = 0.100; Figure 7B). For ABG vs PBG abundance, no significant difference was observed (z-score: -1.13, p = 0.130; Figure 8C).

Figure 6: NMDS of Community Composition of Belowground Invertebrates in ABG vs. PBG and By Years Since Burning



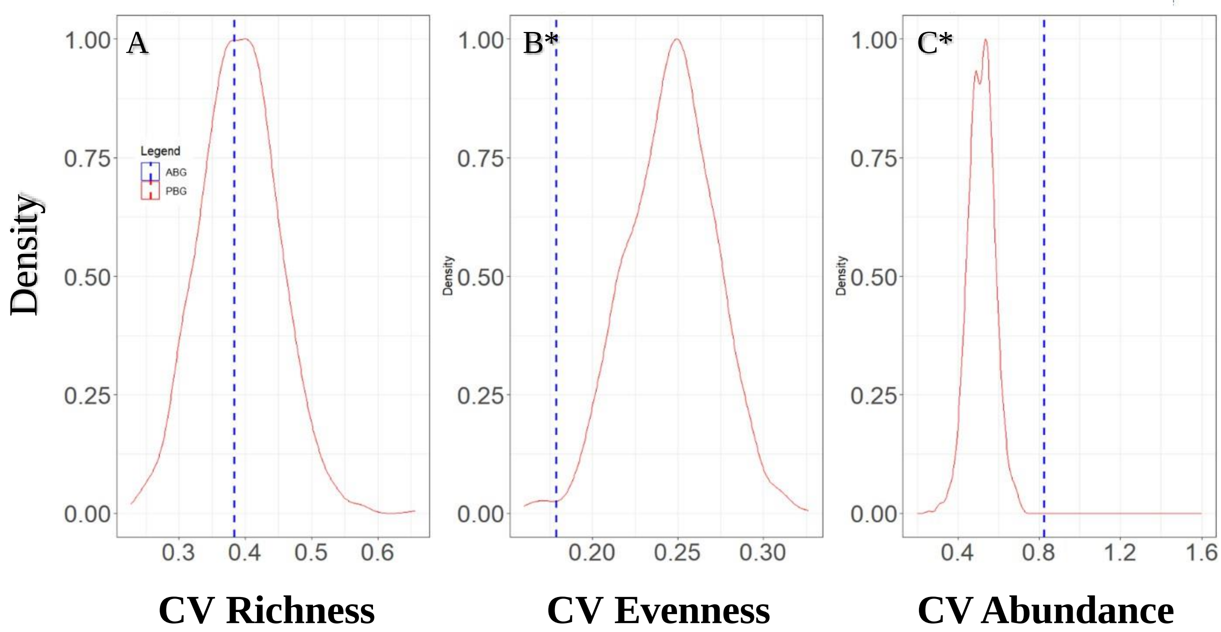
Note. A) NMDS of ABG vs. PBG plots. B) NMDS of Years Since Burn Plots. Each dot is representative of a plot with treatment being defined by the associated legend. Circles represent 95% confidence intervals for the respective treatments. I observed a difference between mean composition of years since burn treatments (B) but did not observe any other significant differences across both our panels (A, B).

Figure 7: Density Graph of Mean Richness, Evenness and Abundance for Belowground Invertebrates



Note. Density graph of mean richness ABG vs PBG B) Density graph of mean evenness ABG vs PBG. C) Density graph of mean abundance ABG vs PBG. Red lines are representative of PBG means whereas blue lines are presentative of ABG means. For richness (A), I saw a significant difference towards ABG. However, I did not see a significant difference between treatments in evenness (B) or abundance (C).

Figure 8: Density Plots Comparing Mean CV Richness, Evenness and Abundance.

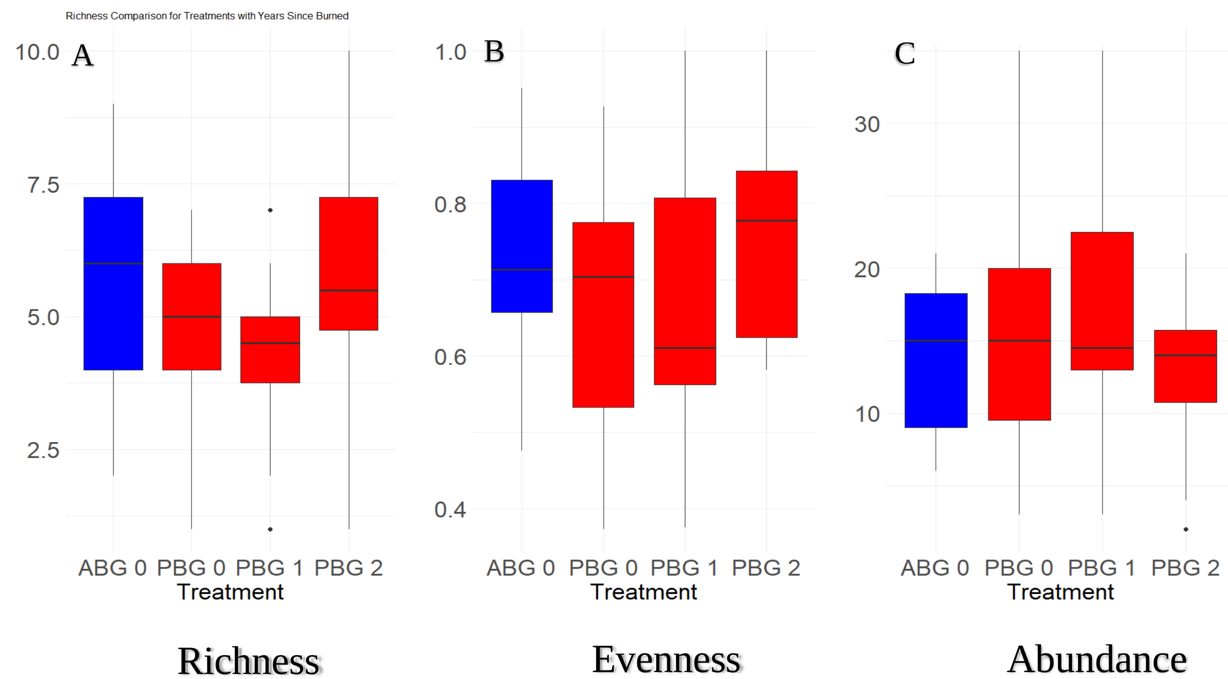


Note. Density plots comparing mean CV richness (A), evenness (B), and CV abundance (C) of belowground invertebrates between ABG (blue dashed lines) and PBG (red curves) in 2021. Significant differences were assessed at $p<0.05$. For belowground CV richness (A), we did not see a significant difference between treatments. However, for CV evenness (B) we saw a significant difference towards PBG and in CV abundance (C) we saw significant differences towards ABG.

Coefficient of Variance (CV): I compared ABG vs PBG coefficients of variation for richness, evenness, and abundance. We saw no significant difference between ABG and PBG for richness (z-score = -0.13, p = 0.894; Figure 8A). However, we did see a significant difference between evenness (z-score = -2.60, p = 0.009; Figure 9B), and abundance (z-score = 4.76, p < 0.001, Figure 9C).

Years Since Burn: A statistically significant difference in belowground mean community composition was observed across watersheds based on the number of years since burning ($F_{3,49}$ = 1.5242, p = 0.042; Figure 6B). However, no significant difference was observed in community variance among the watersheds based on years since burning ($F_{3, 49} = 0.773$, $p = 0.53$; Figure 6B). Additionally, for years since burn, no statistically significant difference was observed for richness ($F_{3,50} = 0.89$, $p = 0.453$; Figure 9A) or evenness ($F_{3,47} = 0.52$, $p = 0.672$; Figure 9B). There was no significant difference for abundance ($F_{3,50} = 0.86$, $p = 0.466$; Figure 9C).

Figure 9: Boxplot of Years Since Burn for Belowground Invertebrate Richness, Evenness and Abundance



Note. ABG 0 (zero years since burned) is represented in blue. PBG 0, PBG 1, PBG 2 (0, 1 and 2 years since burn respectively) are represented in red. A) Boxplot representing belowground richness across burn treatments. B) Boxplot representing belowground evenness across burn treatments. C) Boxplot representing belowground abundance across burn treatments. No significant difference were observed across any panels (A-C).

Discussion/Conclusion

Understanding the dynamics of belowground communities is essential for comprehensively assessing ecosystem health and resilience. In this study, I examined the effects of different treatments (ABG vs. PBG) and years since burn on belowground community composition and abundance of morphospecies. Overall, my results do not support the concept of increased vegetative heterogeneity promoting biodiversity or variability in belowground invertebrate communities. In fact, I recorded increased belowground invertebrate richness in ABG compared to PBG, further indicting a lack of supportive for my hypothesis. As a whole, however, my results are primarily indicative of no difference, rather than a net trend towards PBG or ABG.

A range of factors likely influence belowground communities of invertebrates, including soil characteristics, vegetation type, and land management practices. Fire also plays a significant role, as it can directly affect soil properties such as temperature and moisture, which in turn impact belowground invertebrate communities (Kral et al. 2016). Some larvae may experience improve larvae survival or emergence rates as a result of fire (Kral et al. 2016). However, survivability is quite variable and is based on many factors including, but not limited to, life stage and mobility (Kral et al. 2016). Therefore, the impacts of fire on belowground invertebrate communities are complex and may be ecosystem dependent.

Many of the previously mentioned factors might offer an explanation for lower richness in PBG when compared to ABG. They may also explain the non-statistically significant trend in which evenness in ABG is higher than PBG. This may not be surprising in the context of the literature, which indicates that fire may have a positive impact on larvae (Kral et al. 2016). However, this does not necessarily mean that ABG is beneficial for invertebrates overall, nor that it is preferable from a conservation perspective.

A lack of heterogeneity in response across years since a burn in belowground invertebrates could stem from several factors. Firstly, the response of belowground communities to fire disturbance may vary depending on the composition and life history traits of the invertebrates present (Kral et al. 2016). Some invertebrates may be adapted to quickly recolonize burnt areas, while others may take longer to establish or may not be able to recolonize at all. Additionally, belowground processes such as decomposition rates and nutrient cycling may be less immediately affected by fire compared to aboveground processes, leading to a delayed or muted response in belowground invertebrate communities. It is also possible that soil acts as an insulator to the heat produced by fire, protecting belowground invertebrate communities from being directly impacted. Furthermore, it's possible that the impacts of fire on invertebrates are quantifiable only beyond the morphospecies level.

The outcomes of this study offer crucial insights into the intricate relationships between vegetative heterogeneity, fire, and belowground invertebrate communities. Understanding these relationships provides us with important insights that can be utilized by land managers to achieve both conservation and production goals. Furthermore, these insights provide us with a more deepened understanding of heterogeneity and its impact on belowground invertebrate communities. These findings have significance for not only grassland ecosystems, but for virtually any ecosystem where belowground invertebrates are present.

CHAPTER IV: THESIS CONCLUSION

This investigation into the effects of alternative fire-grazing management on belowground grassland invertebrate biodiversity at the Konza Prairie Biological Station represents a significant contribution to the understanding of heterogeneity from fire-grazing interactions as well as their dynamics specifically within grassland ecosystems. Through a meticulous examination of above- and belowground invertebrate communities under different management strategies, this study sheds light on the complex interactions between fire, grazing, and biodiversity.

The findings of this study do not unequivocally support the initial hypothesis that increased vegetative heterogeneity resulting from patch burn grazing (PBG) would lead to higher levels of belowground invertebrate biodiversity compared to annual burning and grazing (ABG). However, I do see increased mean and variability of aboveground community composition in PBG, suggesting that heterogeneity is more strongly influencing aboveground communities overall, rather than summary metrics of composition such as species richness. While there were no statistically significant differences in belowground mean and variance for community composition between ABG and PBG treatments, the observation of higher variability in the aboveground dataset this provides support for the idea that increased heterogeneity will increase invertebrate variability.

It is crucial to interpret these findings within the broader context of grassland ecosystem dynamics. The lack, or presence, of significant differences in community composition or biodiversity among plots within each treatment may not be solely attributable to the management strategy employed. Instead, a myriad of factors such as soil characteristics, vegetation type, and other environmental variables may interact in complex ways to shape belowground biodiversity.

Furthermore, only one year out of three observed below normal levels of precipitation. It is possible that one of my management styles may perform better under conditions with temporally variable environmental stresses. This could be important in regard to conservation, with land managers desiring practices that allow for ecosystem resilience. This highlights the need for long-term monitoring and research to elucidate the cumulative effects of fire and grazing on above and belowground invertebrate biodiversity.

Despite the insights gained from this study, it is essential to acknowledge its limitations. The study's focus on a single geographic location and relatively short duration may limit the generalizability of the findings. Future research should aim to investigate these dynamics over larger spatial scales and longer timeframes to capture the full extent of variability in belowground invertebrate communities.

In conclusion, this thesis underscores the complexity of invertebrate communities and their responses to fire-grazing management in grassland ecosystems as a direct way to understand heterogeneity in a broader context. While PBG may offer certain benefits in terms of promoting landscape heterogeneity, its effects on invertebrate biodiversity and variability are mixed. Continued research in this area is imperative for informing evidence-based land management strategies aimed at conserving grassland biodiversity and ecosystem functioning in the face of ongoing environmental change.

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