150

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Effect of prescribed fire on plant α- and β-diversity and their spatial patterns in mesquite-oak savanna

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Abstract

Fire is a fundamental process in the rangelands of the Great Plains, and dynamic mosaics of areas burned at different times are essential for maintaining and supporting biodiversity, livestock production, and wildlife habitats, among other ecosystem services. The semi-arid rangelands of the Southern Great Plains typically have strong spatial heterogeneity in vegetation structure, which can affect the pattern of fire and its impact on plant diversity and spatial pattern but have received little attention in research. In this study, we investigated the effect of prescribed fires on plant α- and β-diversity and their spatial pattern in a mesquite-oak savanna landscape in the Edwards Plateau. In an 182.2 ha (450-acre) burn unit in a research ranch managed with a pyric herbivory regime, we sampled 288 randomly located 1-m^2 plots in both the pre-fire and post-fire seasons and collected data on plant species composition and abundance. We also mapped the areas burned within the burn unit using high-resolution (21 cm) multispectral data and machine-learning classification. Plant α-diversity was measured using species richness, evenness, and Shannon's H index, and β-diversity using the Sørensen index of dissimilarity and its turnover and nestedness components. Our results show that the prescribed fire appeared to promote α-diversity in soils with sufficient moisture but weakened the overall spatial structure of α-diversity. The prescribed fire negatively affected β-diversity, likely through both direct effects of fire on plants and indirect effects of intensified selective grazing after fire. Differential changes in species composition of forbs and grasses had an important influence on β-diversity. Burn pattern significantly influenced spatial patterns of post-fire β-diversity. These complex effects of prescribed fire on plant α- and β-diversities and their spatial pattern likely have implications for these heterogeneous savanna landscapes' ecosystem functions and services.

Introduction

Previous research on the interaction of fire and grazing (Fuhlendorf et al. 2006, 2009, 2017) has primarily focused on areas burned uniformly in the Southern Great Plains. However, processes in patchy burns across heterogeneous wooded savanna rangelands with variable herbaceous fuel continuity and seasonal precipitation remain underexplored, particularly regarding their influence on α- and β-diversity, including turnover and nestedness components (Anderson et al. 2011; Baselga 2012; Heydari et al. 2017). Plant diversity, often measured through α-diversity (e.g., species richness within a specific area) and β-diversity (variation in species composition between areas), plays a crucial role in ecosystem dynamics. Fire is a key ecological driver that shapes species composition, ecosystem stability, and resilience, yet its spatial effects on plant diversity across different soil types (Winter et al. 2011) remain unclear. Studies have shown that fire influences ecosystem stability and species composition spatial variability (McGranahan et al. 2018), affecting turnover and nestedness components of β-diversity (Anderson et al. 2011; Baselga 2012; Heydari et al. 2017). By analyzing pre- and post-fire spatial patterns, we can better understand fire's role in diversity changes and its broader implications for ecosystem, function, structure, and services, particularly in maintaining habitat heterogeneity and species diversity in fire-adapted semi-arid rangelands. This study addresses these gaps by examining patchy prescribed fires in mesquite-oak savannas. Specifically, it aims to 1) quantify burn patterns and changes in diversity, 2) assess the magnitude and spatial variability of these changes, and 3) determine how burn status spatially influences diversity. These findings will advance the understanding of fire's role in shaping plant diversity and ecosystem dynamics in semi-arid rangelands.

Methods

This study was conducted on a Texas A&M AgriLife Research ranch (Fig. 1a) in the eastern Edwards Plateau of Texas (30.809670 N; -99.865701 W). The study area includes two nearby pastures, where prescribed burns were conducted in February 2019 (Fig. 1b). The monthly rainfall pattern around the study period (2018-2019) is shown in Figure 1c.

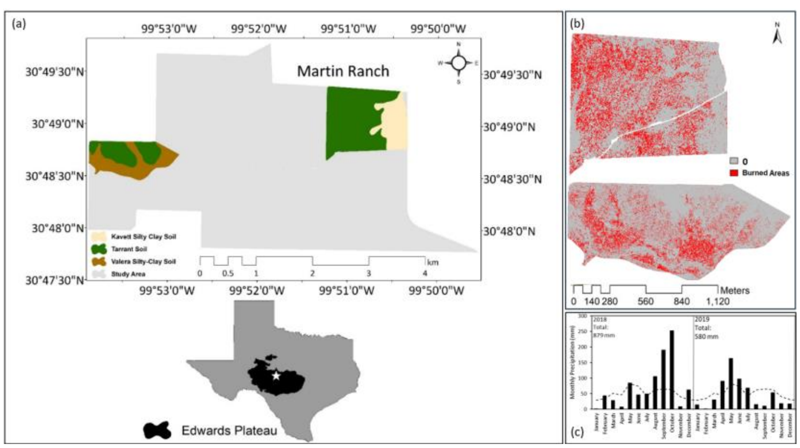

Figure 1. The (a) study area in the ranch with the map of soil types in the study area (TA = Tarrant, VaB = Valera, KaB = Kavett), (b) the maps of burn patterns from the burn units, and (c) the monthly precipitation (bars) from 2018 to 2019 compared to PRISM 30-yr standard (dash line) at the study site in the eastern Edwards Plateau of Texas.

Field data was collected in September-December 2018 (prefire) and September-December 2019 (postfire). Quadrat placement was randomly stratified by soil type, with 120 quadrats in each dominant (TA and VaB) and 48 in the secondary (KaB) soil series, consistently for both periods. Maps of burn status (burned, unburned) were developed by classifying high-resolution (21-cm) aerial imagery using the random forests

(RF) classification method. The α-diversity at each sampling point was calculated based on the percent cover data of plant species for prefire and postfire seasons. The incidence-based β-diversity (β.SOR, β.SIM, and β.SNE) was calculated for all pairs of sampling points (Baselga 2012; Baselga & Orme 2012). The prefire to postfire change in each diversity measure (xΔ = post - pre) was the dependent variable, and soil type and burned status were the fixed factors of the two-way ANOVA models with Bonferroni corrections on the adjusted p-value. To test normality and homogeneity of variance before ANOVA, Shapiro-Wilk and Levene's tests were run on the data without transformations. For both α-diversity and β-diversity, simple Mantel (xD), cross-Mantel tests (xB, $X_{pre}X_{post}$), and partial Mantel tests (X_{post}D.B) were performed to assess the spatial structure and cross-correlation in terms of spatial continuity; where D is a spatial distance matrix (Euclidean distance between sampling points and B is a variable distance matrix (absolute value of the difference in burn status between sampling points).

Results and Discussion

Prefire and postfire measures of α-diversity and their spatial patterns

Fire likely promoted α-diversity in soils with sufficient moisture as changes were 3 times more negative in unburned areas, especially in KaB soil with higher water-holding capacity (Fig. 2ab). There were significant differences in prefire to postfire changes α-diversity (Shannon index, p = 0.014) of all species between burned and unburned areas in the KaB soils alone or the study area (Fig. 2a). As shown in Figure 2b, the changes in α-diversity were primarily driven by annual and perennial forbs. The most notable differences between the burned and unburned areas were in the cool and warm season annuals and the warm season perennial forbs (Fig. 2c).

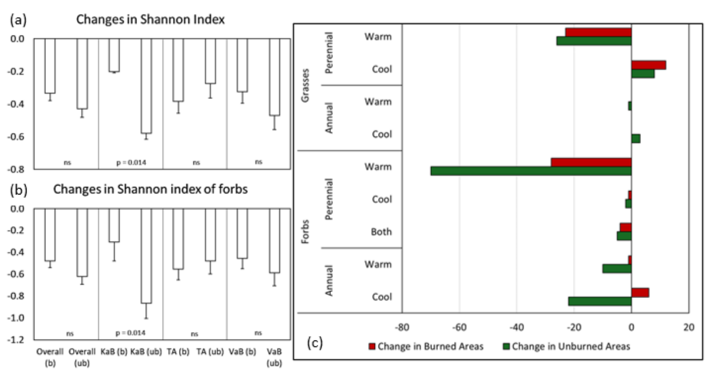

Figure 2. Prefire to postfire change in α-diversity in burned [B] and unburned [UB] areas overall and within each of the soils for (a) all species and (b) forbs. (c) Average changes in species frequency by functional groups in burned and unburned areas in KaB soil.

The spatial pattern of the changes in α-diversity from α_{pre} to α_{post} season in the study area is complex. Moreover, the spatial continuity of α-diversity weakened after the fire (Mantel's r = -0.028, p = 0.038). Still, the spatial pattern remained consistent as both $\alpha_{pre}\alpha_{post}$ spatially correlated (Mantel's r = 0.117, p = 0.017) and α_{post} correlated with burn pattern (Mantel's r = 0.038, p = 0.002). The spatial pattern of the burned areas within the study area was complex, influenced by the strong spatial heterogeneity of the vegetation and fuel characteristics of these semi-arid savannah landscapes (Bradstock, 2010; Singh et al., 2018). As these burned patches were interspersed with unburned areas, the varying changes in α-diversity between burned and unburned areas logically weaken the spatial structure in terms of spatial continuity (the correlation between the differences in variable values and the distance separation between sampling points). These results suggest that prescribed fires likely diminish the spatial structure of α-diversity, at least in the short term, given the typically heterogeneous burn patterns in these diverse savannah landscapes. The spatial pattern of α-diversity can likely be sustained in areas with low soil moisture, where the effects of fire and the changing weather patterns on α-diversity align similarly.

Prefire and postfire measures of β-diversity

Overall, fire negatively impacted β-diversity as the average values of β-diversity (β.SOR and β.SIM) decreased significantly ($p < 0.001$), while that of species nestedness (β.SNE) increased significantly (Fig. 3a). β-diversity measures between sampling points within the burned areas decreased more than those between points within the unburned areas (Fig. 3b). We observed a decline in overall differences in species composition within burned areas. Meanwhile, unburned areas exhibited slightly higher β-diversity, primarily affected by dry-down conditions (Fig. 3b).

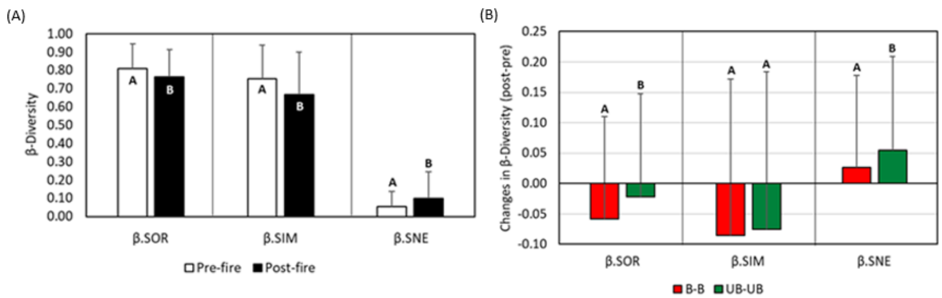

Figure 3. (A) The prefire and postfire β-diversity measures (mean±std), and (B) the change (mean±std) for pairs of sampling points within burned (B-B) and unburned (UB-UB) areas.

Beta diversity decreases after a fire, likely due to reduced herbaceous species frequency, increasing common perennial bunchgrass species (e.g., *Nassella leucotricha*), and stimulating post-fire grazing, which altered its spatial structure. Mantel test showed significant alterations in the spatial structure from β_{pre} (Mantel's $r = 0.019$, $p = 0.05$) to β_{post} (Mantel's $r = -0.021$, $p = 0.03$) β.SOR, but not in either of its components (β.SIM and β.SNE). There was no spatial correspondence between $\beta_{pre}\beta_{post}$ spatial patterns, but β_{post} (Mantel's $r = 0.038$, $p = 0.002$) and its components had a significant spatial correlation with the burn pattern. In terms of β_{post}D.B, spatial structure in β-diversity (β.SOR) remains. These results suggest that the combined effect of burn pattern and dry-down conditions from lack of precipitation influenced the spatial structure of β-diversity.

Conclusions and Implications

Our study highlights the important dynamics of patchy fires on plant diversity during dry-down periods in Mesquite-Oak savanna landscapes. Fire modifies plant diversity within burned areas by influencing α-diversity through soil moisture availability, reshaping species composition based on burn pattern, and altering spatial patterns in response to weather conditions and grazing intensity. Postfire, α-diversity increased based on soil moisture characteristics, while β-diversity declined, disrupting the prefire spatial structure. These findings underscore the ecological ramifications of postfire conditions on plant community dynamics, indicating that heterogeneous fires promote species replacements. These shifts, influenced by interactions among fire, soil, grazing, and weather, reveal the dynamic role of patchy fire in reshaping herbaceous biodiversity. This study provides a foundation for refining prescribed fire practices that promote biodiversity and ecosystem resilience. Also, it provides insights for adaptive fire management strategies considering soil and vegetation dynamics and conservation of fire-dependent semi-arid rangelands.

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