Agroforest Syst (2026) 100:152
https://doi.org/10.1007/s10457-026-01524-5

Goats and oaks: applicability of targeted browsing to promote forage quality and conservation outcomes in woodland communities in the Central Hardwood Region of the United States

Gina Beebe · Lauren Pile Knapp · Connor D. Crouch · Dacoda Maddox · Brian Davidson · Michael Stambaugh · Daniel C. Dey

Received: 26 January 2026 / Accepted: 21 April 2026

Abstract Open oak woodlands, once dominant across the Central Hardwoods Region of the United States, have been largely replaced by dense, closed-canopy forests following decades of fire suppression and land-use change. Silvopasture, the intentional integration of trees, forages, and livestock, may offer economic incentives for private landowners to restore these degraded woodlands while producing marketable livestock. Targeted goat browsing is a potential tool for shifting dense woodland systems toward open, silvopasture conditions. However, limited information exists on how browsing influences plant community composition or how it compares to prescribed fire for restoration and production objectives. We conducted a three-year field study in oak woodlands of the Missouri Ozarks to evaluate the effects of seasonal targeted goat browsing (spring, fall, or combined dormant+fall), prescribed fire, and their combination on forage composition, woodland indicator species, and floristic quality metrics. Spring browsing was the most effective treatment for promoting high-quality forage, shifting communities toward warm-season grass dominance while maintaining legume cover and reducing forb abundance. Importantly, spring browsing achieved these benefits without degrading floristic quality or reducing woodland indicator species. Prescribed fire increased species richness and woodland indicators but promoted forb-dominated communities rather than grass–legume forages. The dormant bud+fall browse treatment produced the least desirable outcomes for silvopasture, suppressing both herbaceous and woody vegetation. These results demonstrate that appropriately targeted browsing can support both ecological integrity and forage production, challenging assumptions that livestock grazing and woodland conservation are incompatible.

Keywords Silvopasture · Goats · Prescribed fire · Floristic quality · Plant community composition · Open forests

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10457-026-01524-5.

G. Beebe (✉)
Center for Agroforestry, University of Missouri, 203 Natural Resources Building, Columbia, MO 65211, USA
e-mail: gbeebe@missouri.edu

G. Beebe · M. Stambaugh
School of Natural Resources, University of Missouri, 203 Natural Resources Building, Columbia, MO 65211, USA

L. P. Knapp · C. D. Crouch · D. Maddox · D. C. Dey
Northern Research Station, USDA Forest Service, 202 Anheuser-Busch Natural Resources Building, Columbia, MO 65211, USA

B. Davidson
Mark Twain National Forest, USDA Forest Service, 401 Fairgrounds Road, Rolla, MO 65401, USA

Introduction

Mature, second-growth hardwood forests dominated by oak species (*Quercus* spp.) are common within the Central Hardwoods Region of the United States (Fei et al. 2011; Hanberry and Nowacki 2016). These forests primarily established following exploitative timber harvest and intensive land clearing for agriculture in the early 1900 s, resulting in a predominantly even-aged forest landscape that is aging uniformly (Shifley et al. 2014). These past land-use practices followed by decades of little management have produced forests that are degraded and uncharacteristically dense. Open woodlands were once dominant in the region (Hanberry and Abrams 2018; Nuzzo 1986), driven by frequent surface fire which promoted open canopies and abundant ground flora (Pile Knapp et al. 2024). These once open but now degraded forested lands offer opportunities for large-scale management programs focused on reopening forest structure and promoting desirable ground flora, typically through application of prescribed fire and thinning to reduce tree density. For such management programs to gain traction on privately owned land, economic incentives may be necessary. This can be achieved by diversifying the benefits beyond ecological values, such as incorporating livestock production and generating timber revenue.

The majority of forested land in the Central Hardwoods Region is privately owned (Oswalt et al. 2014). This places the responsibility for forest management largely on small-scale land stewards. For example, approximately 83% of Missouri's forested lands (totaling 5.1 million ha) are privately owned (Missouri Department of Conservation 2018). Most of these forested lands have likely undergone decades of fire suppression and other anthropogenic disturbances that have led to midstory densification and suppressed herbaceous layers (Hanberry et al. 2014). Given the prevalence of private lands, meaningful management of forests in the region requires adoption of appropriate practices by private landowners. Limitations to forest management may be biological (e.g., lack of understanding of biological response to management action) or social (e.g., lack of incentive or resources to manage appropriately) (Dey et al. 2019; Webster et al. 2018). Although considerable research has been conducted to address forest management challenges relevant to contemporary forest conditions, best practices are often not used on private lands. Private landowners are resistant to engage in conventional forest management activities without incentive of profit (Khanal et al. 2017).

Silvopasture is the intentional integration of trees or shrubs, forages, and livestock that may offer numerous ecological and agricultural benefits for private landowners. These benefits include improved animal performance due to shade and wind protection, diversification of forage options, an extended forage growing season, brush removal or suppression, income diversification, and increased biodiversity (Cubbage et al. 2012; Karki et al. 2022; MacFarland et al. 2025). Targeted browsing, defined as the use of livestock to achieve specific vegetation management objectives rather than the livestock production goals characteristic of conventional and prescribed grazing systems (Bailey et al. 2019), may serve as a critical first step in transitioning degraded hardwood forests toward productive silvopasture systems. When combined with prescribed burning, targeted browsing may reopen forest structure, increase native ground flora coverage and abundance, and ultimately create conditions suitable for a silvopasture system that is both ecologically and economically beneficial. Because silvopasture systems benefit from partial canopy retention rather than complete woody removal, targeted browsing may reduce midstory stems while simultaneously producing marketable livestock—offering economic returns that fire treatments cannot provide.

Goats (*Capra hircus*) are small ruminants that preferentially consume woody browse, making them well-suited for woodland silvopasture. Goats preferentially target palatable plants while avoiding unpalatable plants and browse plants up to 2 m or more when standing or climbing (Lovreglio et al. 2014; Manousidis et al. 2016). Goats will browse woody invasive species common to Central Hardwood woodlands including honeysuckle (*Lonicera* spp.) and multiflora rose (*Rosa multiflora* Thunb.; Beebe 2021), suggesting the potential for the removal of undesirable plant species while maintaining native and herbaceous plant diversity.

In the United States, little information is available on how to simultaneously manage goats for production and ecological benefit. Most goat research focuses on brush management or invasive species suppression (Launchbaugh and Walker 2006). Less attention has been given to the impact of goats on plant community composition or their use in silvopasture and conservation management. Additionally, most studies have concentrated on planted silvopasture systems, demonstrating significant potential for silvopasture as a successful enterprise that also provides ecosystem services (Karki et al. 2022).

The widespread assumption that productive agricultural lands must sacrifice ecological integrity, such as minimal plant diversity and conservation value, is increasingly challenged by agroforestry systems which aim to balance production and conservation (Jose 2009; Torralba et al. 2016). There are instances, both historically and currently, where ecological damage has occurred due to overgrazing by domestic livestock or unmanaged, feral ruminants (Campbell and Donlan 2005; Coblentz 1978; Fleischner 1994). However, these impacts may reflect inappropriate management practices rather than inherent incompatibility between livestock and natural communities (Hester et al. 2000; Rosa García et al. 2012), leading to a potential bias against livestock in conservation contexts. Consequently, excluding large herbivores has resulted in unbalanced ecological dynamics. (El Aich and Waterhouse 1999). When appropriately managed, studies have shown that the inclusion of goats and other livestock can improve biodiversity, reduce fuel loads and wildfire risk, mitigate invasive woody species, and contribute to local economies (Mancilla-Leyton and Martin Vicente 2012; Rosa García et al. 2012; Tsiouvaras et al. 1989; Úbeda et al. 2019; Valderrábano and Torrano 2000). With growing interest from private and public land stewards in using goats for agricultural production or woodland restoration, it is critical to understand how plant communities respond to targeted browsing and to identify the ecological trade-offs between production and restoration. This understanding will help develop evidence-based management recommendations for silvopasture systems.

To address these gaps, we conducted a three-year field-based experiment to evaluate the application of targeted goat browsing with and without fire to reopen degraded forests and improve ground flora conditions including forage composition and quality, native conservation value, and community stability as measured by floristic quality indices. Specifically, we examined differences in plant community response to (1) browsing seasonality (spring, fall, or combined dormant+fall), (2) single versus repeated annual browsing events, and (3) browsing events alone and in combination with prescribed fire.

We hypothesized that:

H1 Forage composition: Targeted browsing will increase herbaceous forage coverage, though less pronounced than under prescribed fire, while shifting plant composition toward high-value forage groups (grasses and legumes). Spring browsing will yield the most favorable forage composition because canopy reduction will favor warm-season grass production.

H2 Species-level response: Targeted browsing will maintain woodland indicator species (i.e., native species characteristic of open woodland conditions) coverage while favoring distinct species assemblages compared to fire. We expect browsing to promote grazing-tolerant and/or unpalatable species, while fire treatments will favor fire-adapted woodland flora.

H3 Floristic Quality and Community Stability*:* Management treatments will increase plant species richness and diversity but may simultaneously decrease floristic quality metrics (mean C-value, FQI) through the colonization of disturbance-adapted species. Single browsing treatments will maintain higher floristic quality and perennial:annual ratios than either compounded browse treatments or fire treatments.

Methods

Site description

This study utilized data from a woodland restoration experiment at the Onyx Project site, Mark Twain National Forest, Missouri, USA (Beebe et al. 2024). The site lies within the karst topography of the Ozark Highlands and is an oak-dominated woodland, with white oak (*Quercus alba* L.), post oak (*Q. stellata* Wangenh), and black oak (*Q. velutina* Lam.) in the overstory. The midstory included black hickory (*Carya texana* Buckley), black gum (*Nyssa sylvatica* Marshall), American plum (*Prunus americana* Marshall), fragrant sumac (*Rhus aromatica* Aiton), and blackberry (*Rubus* spp.), while common climbing vines were Virginia creeper (*Parthenocissus* *quinquefolia* L.), poison ivy (*Toxicodendron radicans* L.), and grapevine (*Vitis* spp.). Herbaceous understory vegetation included fireweed (*Erechtites hieraciifolius* L.), hairy sunflower (*Helianthus hirsutus* Raf.), and elm-leaved goldenrod (*Solidago ulmifolia* Muhl. Ex Willd). Forage plants at this site consisted primarily of legumes including American hogpeanut (*Amphicarpaea bracteata* L.), tick trefoil (*Desmodium* spp.), partridge pea (*Chamaecrista fasciculata* Michx.), and lespedezas (*Lespedeza* spp.); cool-season grasses including hairy woodland brome (*Bromus pubescens* Muhl. ex Willd.) and Virginia wildrye (*Elymus virginicus* L.); and warm-season grasses including panicgrasses (*Dichanthelium* spp.), little bluestem (*Schizachyrium scoparium* Nash), and eastern gamagrass (*Tripsacum dactyloides* L.).

Following overstory thinning in 2012 and mastication in 2017, the site had an open canopy (approximate basal area of 17.3 m^2 ha^{-1}) but with a well-developed dense, multi-stemmed woody midstory and limited herbaceous cover by the time the study was initiated in 2019.

Regional climate data (1888 to 2021) indicate a mean annual precipitation of 126 cm, with peak rainfall occurring in May, and a mean annual temperature of 13.1 °C (−2.2 °C in January; 23.3 °C in July). In 2019, the nearest weather station in Vichy, Missouri (~24 km north) recorded 106 cm of precipitation and 22 days exceeding 32 °C, with no drought conditions (NOAA 2019). In contrast, 2022 experienced 47 days above 32 °C, total precipitation of 85 cm, and drought conditions ranging from D0 (abnormally dry) to D2 (severe drought) throughout much of the summer (NOAA 2022; *U.S. NIDIS* n.d.).

Experimental design and treatment methodology

We implemented six treatments in a randomized complete block design with three replicates: spring browse (SB; May), fall browse (FB; September), dormant+fall browse (DBFB; April+September), prescribed fire (Rx; February), spring browse+fire (SBRx), and untreated control (Fig. 1).

Browsing treatments occurred in 2019 and 2021 using mixed meat goat breeds (nannies with kids). Stocking density was not recorded. Because this study evaluated browsing as a vegetation management tool for creating an economically viable silvopasture system, treatment intensity was standardized using utilization targets rather than animal unit metrics. Between 50 and 200 goats were present within experimental units ranging from 1 to 3.2 ha for 36 h to 7 days. To standardize treatment intensity across variable herd and unit sizes, a target utilization threshold of 85% was applied. Goats were contained using temporary electric fencing, with guardian dogs or shepherds providing additional protection. Livestock and management were contracted through Living Lands, LLC, which supplied fencing, water, and rotational oversight. Supplemental feed was provided during dormant bud browsing to maintain animal nutrition while meeting utilization targets.

Prescribed fires were executed in February 2020 and February 2022 before leaf emergence, using hand-ignited strip head fires transitioning to backing fires. Fuel loads consisted primarily of leaf litter, short timelag fuels, and dried warm-season grasses. In 2020, flames reached 0.3–0.6 m at temperatures of 12–20 °C and 25–30% relative humidity with discontinuous burn coverage. In 2022, the burns had better uniformity, reaching flame lengths of 0.6–1.2 m, with temperatures of 21–27 °C and 15–22% humidity, consuming more 1000-h fuels.

Field measurements

Permanent monitoring plots were established in February 2019 prior to treatment implementation. Each experimental unit had four randomly placed 0.08-ha plots. Within each plot, four 1 m^2 quadrats were positioned at 2.2 m N from each subplot center [subplot centers were 8 m from plot center at cardinal bearings (0°, 90°, 180°, 270°)], yielding 288 quadrats across 18 experimental units. In each quadrat, we recorded percent cover of all vascular plant species less than 1 m tall and separately estimated cover for functional groups: forbs, graminoids, sedges/rushes, legumes, woody shrubs, tree seedlings, and vines. Because functional groups were assessed independently, total cover could exceed 100%. Pretreatment data were collected in summer 2019, and post-treatment data in summer 2022.

Data analysis

Plants were categorized into seven functional groups: forbs, grasses, sedges legumes, shrubs, trees, and

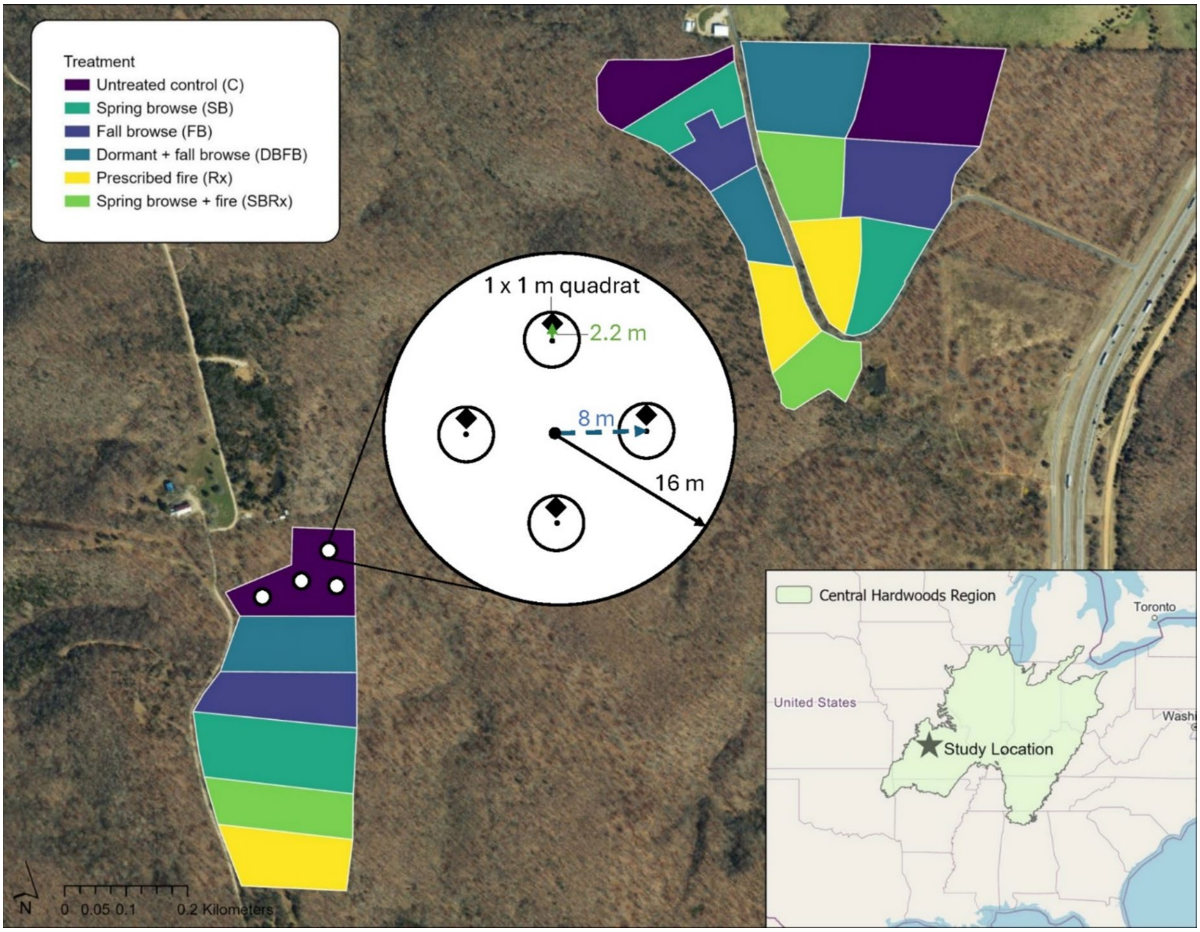

Fig. 1 Map of the study's experimental design, which is a randomized complete block design with three blocks of six treatments (n = 18 experimental units). In each experimental treatment unit, we established four plots, each of which contained four 1 × 1 m quadrats for vegetation sampling

vines. Ferns were excluded due to low occurrence. Forbs, grasses, sedges and legumes were considered herbaceous plants, while shrubs, trees, and vines were considered woody plants. Plants were defined as forage if they belonged to legumes, cool-season grasses, or warm-season grasses and met assumed criteria for nutritive value and persistence based on established nutritional requirements for lactating goats (Briske 1993; NRC 2007; Pierce et al. 2017). Although goats consume woody browse, analyses focused on herbaceous forage species that are relevant to Missouri agricultural systems dominated by sheep and cattle (USDA 2022). Plants were considered woodland indicator species according the expert opinion of Farrington (2009) as published in Kinkead et al. (2013). Coefficient of conservation values (c-values) were sourced from Ladd and Thomas (2015). Floristic quality assessment (FQI) values were calculated using the following equation (Swink & Wilhelm 1979):

$$FQI = Mean\ C\ per\ quadrat x \times \sqrt{Number\ of\ Species\ per\ Quadrat}$$

Cover estimates were recorded as ranges, as such. midpoint values were used. Changes in cover and floristic metrics (species richness, mean C, FQI, Shannon diversity) were calculated as differences between 2022 and 2019 values at the quadrat level.

Treatment effects on vegetation change were analyzed using linear mixed-effects models with treatment as a fixed effect and block as a random effect. Models were fit using the lme4 package (Bates et al.

2015), and statistical significance was determined using the analysis of variance function via the lmerTest package (Kuznetsova et al. 2017). Post-hoc pairwise comparisons were conducted using estimated marginal means with Tukey's HSD adjustment (emmeans package; Lenth 2023). All graphs were created using the ggplot2 package (Wickham 2016).

To identify plant species associated with specific treatments, we conducted species-treatment association analysis using the multipatt function in the indicspecies package (De Cáceres and Legendre 2009). This analysis identifies species that are statistically more abundant and/or frequent in certain treatments compared to others, serving as biological indicators of how treatments affect plant community composition. This analysis was performed using only 2022 post-treatment data ($n=249$ species) with 999 permutations. Species were considered indicators when indicator values exceeded 0.4 ($p<0.05$) and occurred in at least 30 quadrats.

Non-metric multidimensional scaling (NMDS) ordination was used to visualize shifts in forage community composition based on Bray–Curtis dissimilarities. Cover values for each forage functional group (warm-season grasses, cool-season grasses, forbs, legumes) were square-root transformed. We ran a three-dimensional NMDS ($k=3$) using metaMDS in vegan package (Oksanen et al. 2022) with 200 random starts to ensure the solution was stable. Ordination quality was assessed using stress values, with values <0.15 indicating sufficient representation of community patterns (Clarke 1993).

Treatment effects on overall plant composition were tested using PERMANOV (*adonis2*; 999 permutations) with treatment, year, and their interaction as fixed effects. Homogeneity of multivariate dispersion was assessed using *betadisper*, and pairwise comparisons were conducted using adjusted PERMANOVA tests (RVAideMemoire; Herve 2024). Environmental vector fitting (*envfit*; 999 permutations) was used to identify forage functional groups associated with ordination axes. All analyses were performed in R version 4.5.0 (R Core Team 2024).

Results

We evaluated vegetation responses 3 years after initial treatment implementation. Results are presented as changes from pre- (2019) to post-treatment (2022) conditions (calculated as 2022 measurements–2019 measurements), organized by forage composition, woodland indicators and community composition shifts, and floristic quality metrics.

Hypothesis 1: Changes to forage composition

Management treatments produced measurable shifts in forage plant species coverage ($p<0.001$, $F=4.84$; Fig. 2), although no individual treatment differed significantly from the control. However, trends were observed: forage increased in the prescribed fire ($2.3\pm0.8\%$), prescribed fire + spring browse ($2.1\pm0.8\%$), and spring browse ($1.1\pm1.3\%$) treatments while forage decreased in the dormant bud+fall browse treatment ($-6.1\pm0.6\%$).The significant treatment effect observed was that forage coverage was significantly higher in the prescribed fire, prescribed fire + spring browse, and spring browse treatments compared to the dormant bud+fall browse treatment. Both herbaceous and woody plant coverage were significantly affected by the treatments (herbaceous: $p<0.001$, $F=16.85$; woody: $p<0.00001$, $F=6.40$; Fig. 3). Herbaceous plants increased in the fire treatments (prescribed fire + spring browse: $12.7\pm1.5\%$; prescribed fire: $10.2\pm1.35\%$), which were significantly greater than the control. Woody plants significantly decreased only in the prescribed fire treatment (prescribed fire: $27.2\pm1.5\%$). Although not significantly different from the control, there was a notable trend in the dormant bud + fall browse treatment, where all plant coverage (i.e., herbaceous and woody vegetation) was slightly reduced.

The PERMANOVA indicated a significant Treatment × Year interaction ($p<0.001$, $F=2.79$, $R^2=0.053$), demonstrating that plant functional groups changed over time in treatment-specific ways (Fig. 4). The three-dimensional NMDS ordination (stress $=0.138$) adequately represented multivariate community structure, and multivariate dispersion did not differ among treatments (betadisper: $F=1.84$, $p=0.102$), confirming that differences reflect compositional shifts rather than differences in community variability.

The three-dimensional NMDS ordination (stress $=0.138$) outperformed the two-dimensional solution (stress $=0.219$), so we present all three axis combinations to fully capture community trajectories

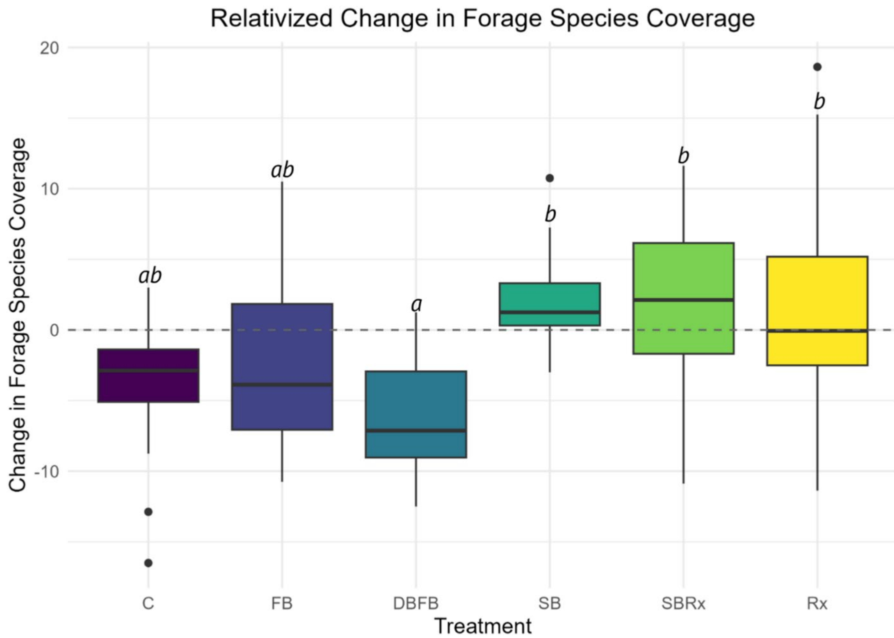

Fig. 2 Change in forage coverage (post-treatment minus pre-treatment values) in the control (C), fall browse (FB), dormant bud + fall browse (DBFB), spring browse (SB), spring browse + prescribed fire (SBRx), and prescribed fire (Rx) treatments. Forage species include legumes and palatable warm-season and cool-season grasses. The dashed line at zero indicates no change. Different letters indicate significant differences among treatments (Tukey HSD, $p < 0.05$)

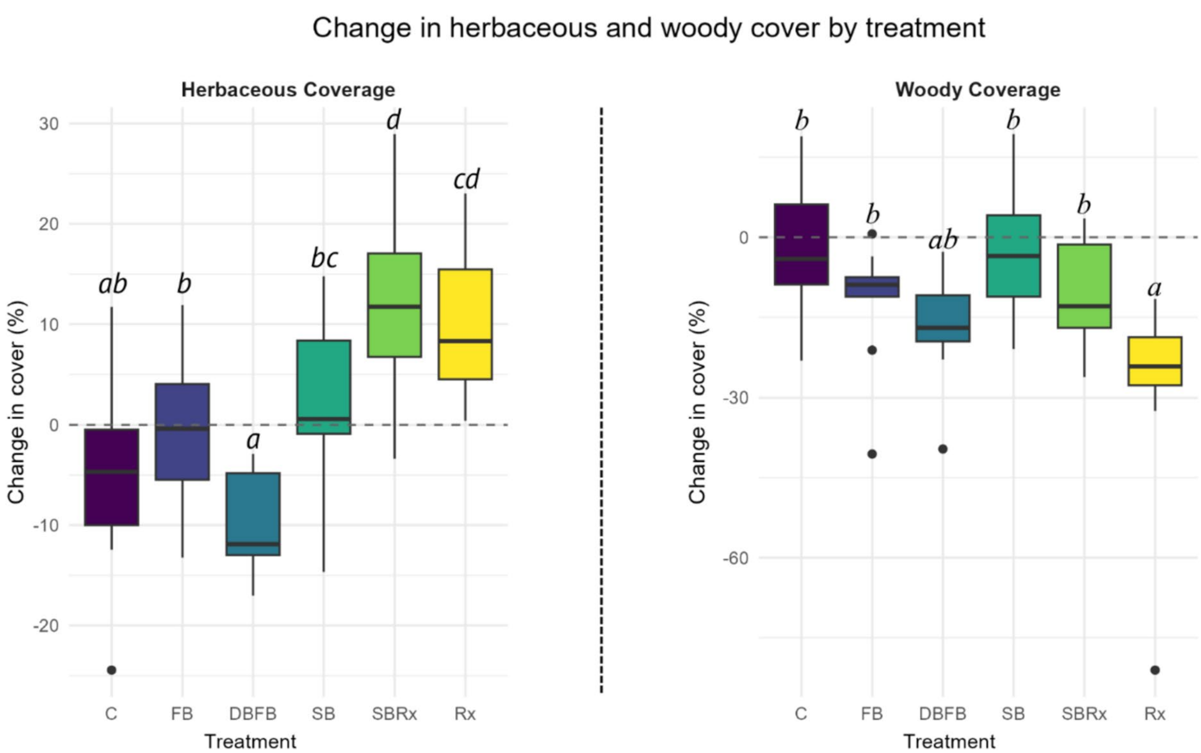

Fig. 3 Change in woody and herbaceous plant species coverage (pre-treatment minus post-treatment value) in the control (C), fall browse (FB), dormant bud + fall browse (DBFB), spring browse (SB), spring browse + prescribed fire (SBRx), and prescribed fire (Rx) treatments. The dashed line at zero indicates no change. Different letters indicate significant differences (Tukey HSD, $p < 0.05$)

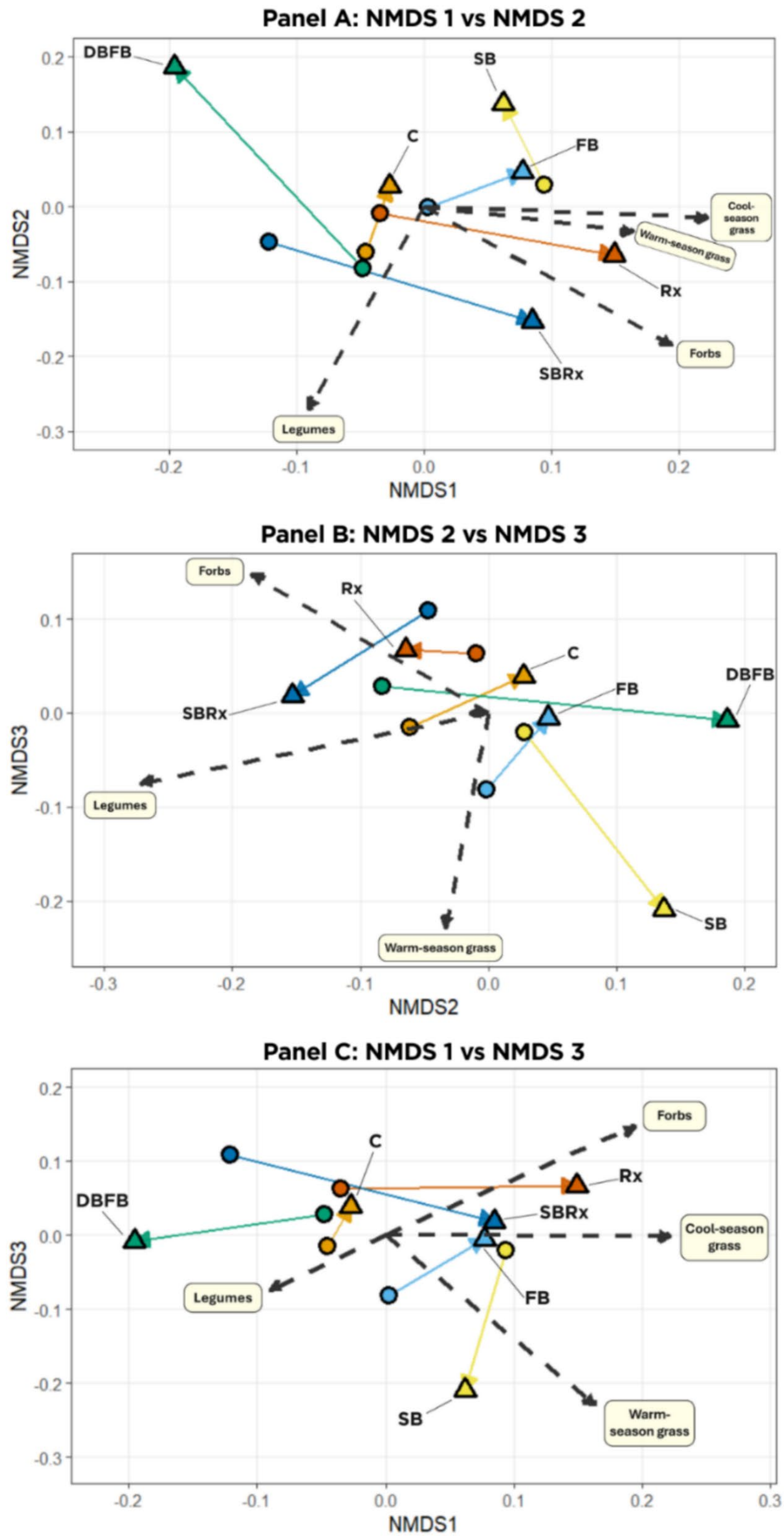

Fig. 4 Three dimensional NMDS ordination of forage function group compassion (stress = 0.138) shown as three two-dimensional projects: **A** NMDS1 vs NMDS2, **B** NMDS2 versus NMDS3, and **C** NMDS1 versus NMDS3. Circles indicate 2019 centroids; triangles indicate 2022 centroids. Treatments are: control (C), fall browse (FB), dormant bud + fall browse (DBFB), spring browse (SB), spring browse + prescribed fire (SBRx), and prescribed fire (Rx) treatments. Dashed vectors show direction of increasing functional group cover. Cool-season grass vector omitted from panel B due to minimal association with those axes

(Fig. 4). Functional groups were distributed across multiple axes: cool-season grasses loaded primarily on NMDS1 ($r^2 = 0.40$, $p < 0.001$), while warm-season grasses loaded on both NMDS1 and NMDS3 ($r^2 = 0.65$, $p < 0.001$). Legumes were most strongly associated with NMDS2 ($r^2 = 0.71$, $p < 0.001$), and forbs loaded across all three axes ($r^2 = 0.76$, $p < 0.001$).

Among all treatments, spring browse produced the most pronounced shift toward a grass-dominated state—a forage structure that is particularly desirable for silvopasture. This shift is most apparent in the NMDS1 vs NMDS3 projection (Fig. 4), where spring browse moved strongly in the direction of the warm-season grass vector. Warm-season grasses increased by 35% (8.86–11.95%), cool-season grasses increased modestly (5.5–7.81%), and legume cover remained stable (4.77–4.45%). Forb cover, however, dropped sharply (10.94–4.10%). This trajectory differed significantly from all other treatments except fall browse (pairwise PERMANOVA, all $p < 0.05$). In contrast, both fire treatments (Rx and SBRx) shifted communities toward forb-dominated conditions, reaching 12.73% and 15.88% forb cover, respectively.

While the ordination revealed clear differences in overall community trajectories, the univariate tests of individual plant groups showed fewer treatment-level differences. Cool-season grass ($p = 0.64$) and warm-season grass ($p = 0.053$) did not significantly vary among treatments, implying that the treatments affected the relative balance of functional groups more than the total amount of grass. Forbs showed strong treatment effects ($p < 0.001$, $F = 20.40$)–both fire treatments significantly increased forb coverage in comparison to the control. Legumes also varied significantly among treatments ($p < 0.001$, $F = 5.46$). Legume coverage significantly increased in the spring browse + prescribed fire treatment in comparison to the control.

Hypothesis 2: Species-level responses

Analysis revealed significant differences in woodland indicator species (Table S1) coverage among treatments ($p < 0.001$, $F = 8.0$; Fig. 5). Prescribed fire alone significantly increased woodland indicator species coverage, consistent with the fire-adapted nature of oak woodlands. Positive trends were observed in the spring browsing (1.37 ± 1.33%) and the spring browsing + prescribed fire (4.99 ± 0.68%) treatments but were statistically similar to the control. In contrast, dormant bud + fall browse showed a negative trend of woodland indicator species.

To assess which plant species were associated with different management practices, we conducted

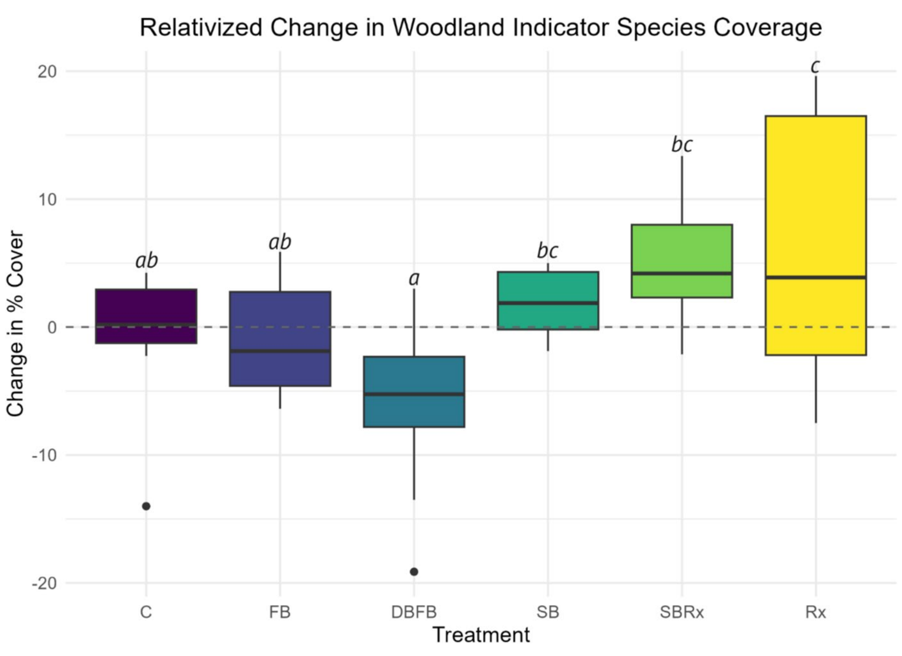

Fig. 5 Relativized change of woodland indicator species coverage from pretreatment to posttreatment conditions in the control (C), fall browse (FB), dormant bud + fall browse (DBFB), spring browse (SB), spring browse + prescribed fire (SBRx), and prescribed fire (Rx) treatments. Different letters indicate significant differences (Tukey HSD, $p < 0.05$)

species-treatment association analysis. This analysis revealed that only 9 of 249 species (3.6%) showed significant treatment associations, and none were exclusive to a single treatment (Table 1). Notably, hairy panic grass (*Dichanthelium implicatum* Sw., C-value = 7), the only conservative species identified as an indicator species, was associated with all browsing treatments ($p = 0.002$). Dittany (*Cunila origanoides* L.), a Missouri woodland indicator species as defined by the Missouri Department of Conservation, showed significant associations with all treatments except spring browse + fire ($p = 0.011$, stat = 0.41). Ruderal species including toxic white snakeroot (*Ageratina altissima* L.) and broomsedge (*Andropogon virginicus* L.) were primarily associated with spring browsing, prescribed fire, and their combination.

Hypothesis 3: Floristic quality and community stability

Management treatments had varying impacts on the life history composition of forbs. Specifically, for annual forbs, the results showed a significant difference ($p < 0.05$; F = 2.94), while for perennial forbs, the results were even more pronounced ($p < 0.001$; F = 6.23; Fig. 6). Generally, annual forbs were sparse in the study area, averaging less than 3% cover in each treatment in 2019, and no treatment significantly affected their coverage. In contrast, for perennials, the prescribed fire treatment alone had a significant effect, resulting in an increase of 7.8 ± 1.45%. Coverage also trended upward in the spring browse (1.23 ± 1.58%) and spring browse + prescribed fire treatments (5.58 ± 1.59%). Both fire treatments and the spring browse treatment showed a significant increase in perennial coverage compared to the dormant bud+fall browse treatment.

Management treatments significantly influenced all analyzed floristic quality metrics: species richness ($p < 0.001$, F = 8.2), Mean C ($p < 0.05$, F = 2.59), Floristic Quality Assessment (FQA; $p < 0.01$, F = 3.7), and the Shannon Index ($p < 0.05$, F = 2.85; see Fig. 7). Species richness significantly increased under fire treatments compared to the control and to the dormant bud+fall browse and spring browse treatments. However, Mean C significantly declined under fire treatments compared to the control. Notably, Mean C was neutral to slightly positive in the dormant bud + fall browse treatments. For FQA, no individual treatment differed significantly from the control, but both fire treatments produced a significantly more positive response compared to the dormant bud + fall browse treatment. The Shannon Index also increased significantly under the prescribed fire treatment compared to the control.

Table 1 Plant species showing significant associations ($p < 0.05$) with one or more treatments based on species-treatment association analysis (multipatt; De Cáceres and Legendre 2009)

Scientific Name	Common name	C-value	C	FB	DBFB	SB	SBRx	Rx	stat	P
Ageratina altissima	White Snakeroot	2	1	0	0	1	1	1	0.553	0.001
Acalypha virginica	Virginia mercury	2	0	1	0	1	1	1	0.543	0.022
Andropogon virginicus	Broom Sedge	2	0	1	1	1	1	0	0.512	0.029
Geum canadense	White avens	2	1	0	0	1	1	1	0.427	0.035
Sanicula canadensis	Canadian Black Snakeroot	3	1	0	0	1	1	1	0.410	0.003
Quercus alba	**White Oak**	4	1	1	1	1	0	1	0.510	0.033
Hylodesmum nudiflorum	Bare-Stemmed Tick Trefoil	4	1	1	0	1	1	1	0.471	0.051
Cunila origanoides	**Dittany**	6	1	1	1	1	0	1	0.408	0.011
Dichanthelium implicatum	Hairy Panic Grass	7	0	1	1	1	1	0	0.454	0.002

Indicator values (stat) range from 0 to 1, with higher values indicating stronger associations. C-values indicate species conservation value: ≤ 3 = ruderal, 4—6 = matrix, ≥ 7 = conservative. Bold species indicate Missouri woodland indicator species as defined by the Missouri Department of Conservation (distinct from treatment-associated species identified by this analysis). Within the control (C), fall browse (FB), dormant bud + fall browse (DBFB), spring browse (SB), spring browse + prescribed fire (SBRx), and prescribed fire (Rx) columns, 0 s indicate a non-significant association while 1 s indicate a significant association

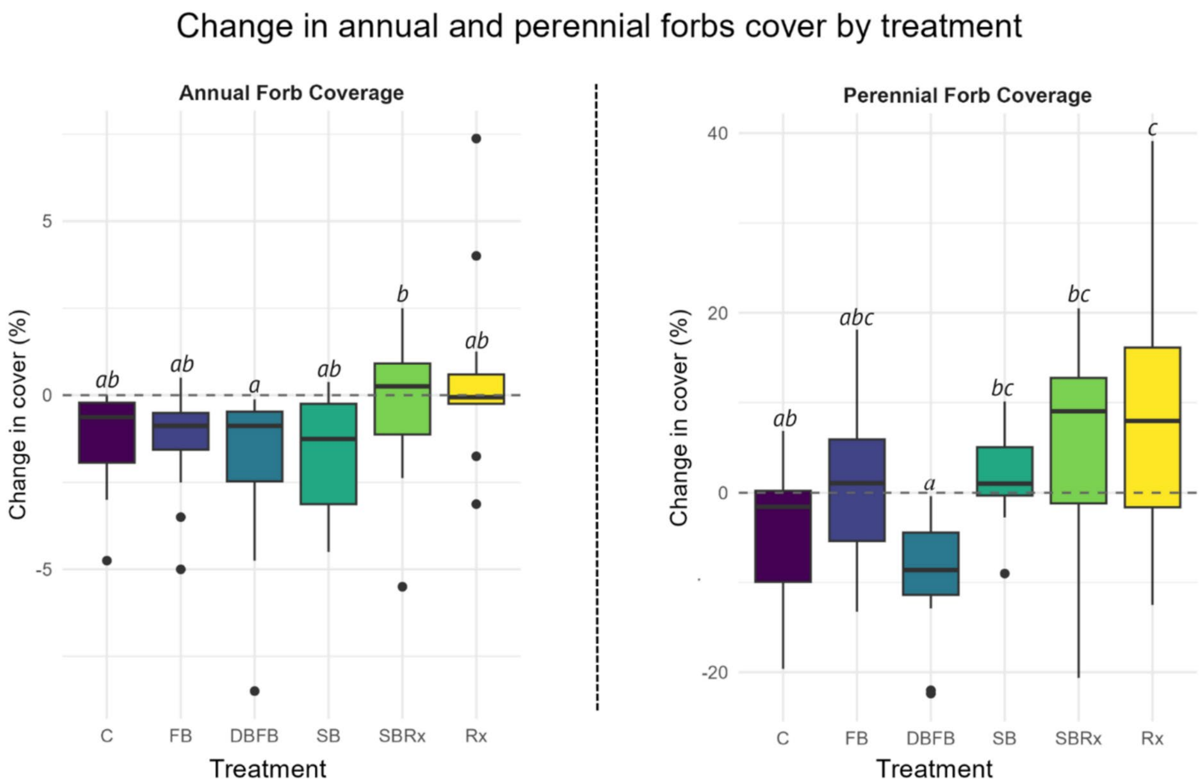

Fig. 6 Change in annual and perennial forb cover from pre-treatment to post-treatment conditions in the control (C), fall browse (FB), dormant bud + fall browse (DBFB), spring browse (SB), spring browse + prescribed fire (SBRx), and prescribed fire (Rx) treatments. Letters indicate significant differences (Tukey HSD, α = 0.05)

Summary table of trade offs—treatment responses to metrics

Discussion

Historically, the Central Hardwoods Region was dominated by open forests—savannas and woodlands with widely spaced canopies, minimal midstories, and abundant ground flora shaped by fire and grazing (Hanberry et al. 2014; Pile Knapp et al. 2024). These formerly open forests are now overly dense with depauperate and often invasive ground flora. Private landowners need a variety of options for stewarding, and creating economic opportunities from, these degraded woodland landscapes. For woodland silvopasture to be economically viable, adequate herbaceous forage must be available and typically includes a mixture of C3 (cool-season) and C4 (warm-season) grasses, which provide complementary seasonal growth patterns and extend forage availability across the growing season (Pierce et al. 2017), and legumes which contribute additional nutritional value through higher crude protein concentrations (Frame et al. 1998).

However, the prevailing management paradigm holds that woodland grazing degrades ecological integrity which has limited this tool to land stewards and producers alike. Our study suggests that targeted browsing with goats may be a viable first step in developing silvopasture systems in degraded woodlands, although the timing and intensity of browsing critically influences whether plant communities shift toward desirable forage conditions or experience suppression.

Treatment effects of forage functional groups

Spring browsing emerged as the most effective treatment for developing silvopasture-quality forage. It

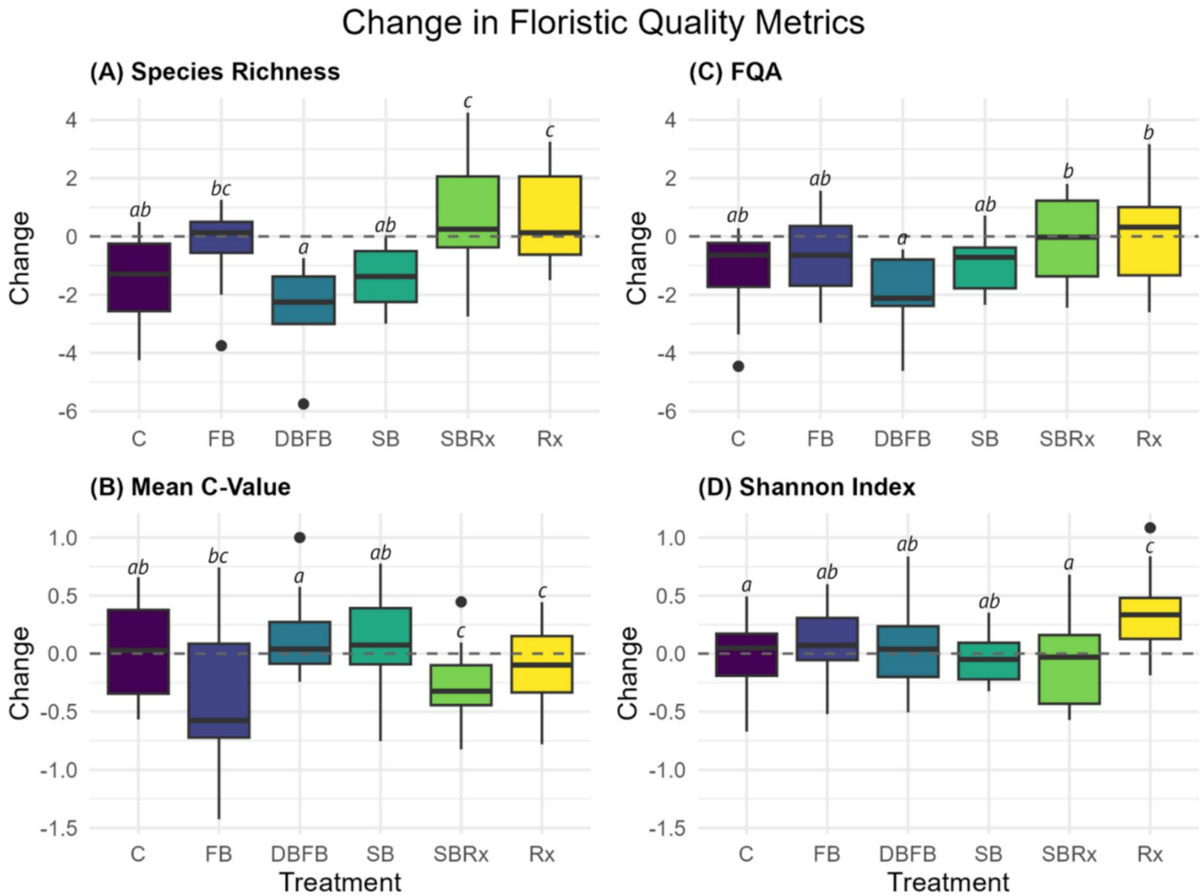

Fig. 7 Change in floristic quality metrics from pre-treatment to post-treatment conditions in the in the control (C), fall browse (FB), dormant bud + fall browse (DBFB), spring browse (SB), spring browse + prescribed fire (SBRx), and prescribed fire (Rx) treatments. Mean relativized change in floristic quality metrics by treatment. **A** Species richness (number of species per plot), **B** mean coefficient of conservatism (C-value), **C** species richness (number of species per plot), and **D** Shannon Evenness Index. Error bars show ± SE. Different letters indicate significant differences (Tukey HSD, $p < 0.05$)

promoted warm-season grasses, maintained legumes, and reduced forb pressure—without degrading floristic quality or woodland indicator species. While cool-season and warm-season grass cover did not differ significantly among treatments, treatments influenced the relative balance of functional groups more than absolute grass abundance. This distinction matters for silvopasture management: spring browsing may not dramatically increase grass cover, but it may shift the balance away from forbs and toward a grass-legume forage base which are desirable and effective conditions for silvopasture systems.

The mechanism behind spring browsing's effectiveness likely involves the timing of defoliation relative to plant phenology. Spring browsing reduces woody midstory cover, increasing light availability in the understory (Beebe et al. 2024). Compensatory growth responses may favor grasses, which possess basal meristems that permit continued leaf elongation following defoliation (Briske 1996; McNaughton 1979). Many forbs, in contrast, rely on apical meristems at shoot tips that are more vulnerable to removal, limiting regrowth when defoliated during active growth (Briske 1996; Crawley 1983). This differential response from grasses and forbs in response to herbivory explains the observed shift toward grass-dominated communities with spring browsing.

Fall browsing revealed a slight positive trend in the composition of cool-season grasses. Woody defoliation in the midstory occurred during the peak growing season of C3 grasses. This, combined with increased light and active plant growth, may have supported compensatory growth. While the results indicate that fall browsing alone may not be the most effective tool for restoration efforts, it could offer producers an expanded opportunity for whole-farm integration and pasture rest without causing significant ecological degradation.

Combining fall browsing with dormant season browsing created a compounding disturbance that suppressed forage production and led to a decline in the cover of all functional plant groups. Dormant browsing in early spring may have stressed emerging plants before they had developed enough leaf area for compensatory regrowth (Briske and Richards 1995). When fall browsing occurred later that year, herbaceous species may have lacked the necessary carbohydrate reserves to recover from this second defoliation event (University of Missouri Extension n.d.). However, this combined browsing treatment did not significantly reduce woody stem density (Beebe et al. 2024), indicating that the midstory canopy recovered after defoliation and continued to shade the understory. These results suggest that dormant + fall browsing may be better suited for site renovation where the goal is to reduce all vegetation before seeding and underscores that the timing and frequency of browsing require careful consideration. Specifically, our results indicate that rotational grazing rest periods common in open pasture management may not be applicable to woodland settings, where plants may require a full growing season to rebuild carbohydrate reserves following defoliation.

Fire treatments increased forb cover while substantially reducing mid- and understory woody stem densities, consistent with prior work in this system (Beebe et al. 2024) and other Central Hardwood woodlands (Hutchinson et al. 2005; Knapp et al. 2015). While an excellent tool for woodland restoration, fire-driven canopy and midstory removal created light and resource conditions that favored rapid forb expansion (Reid et al. 2020), including ruderal species, but did not consistently promote graminoids or legumes. Although some forbs are acceptable in grazing systems, forb-dominated communities typically offer lower forage quality and may include unpalatable or toxic species (Hodgson 1990; Launchbaugh and Walker 2006). For instance, white snakeroot (*Ageratina altissima*), a perennial forb which increased following fire treatments, contains tremetol and is toxic to cattle, sheep, and goats (Beier and Norman 1990). In contrast, spring browsing, despite producing more modest reductions in woody stems (Beebe et al. 2024), appeared to reduce competitive pressure that allowed grasses to capitalize on increased light without triggering strong post-disturbance forb responses.

Species-level and indicator responses

Beyond functional groups, certain plant species serve as ecological indicators, signaling environmental conditions and management trajectories through their life history requirements. In the Central Hardwoods, the Missouri Department of Conservation has identified woodland indicator species that reflect the open woodland conditions both restoration and silvopasture seek to recover. Prescribed fire was the most effective treatment for increasing woodland indicator species coverage, consistent with the fire-adapted ecology of Central Hardwood woodlands (Hanberry and Abrams 2018; Nuzzo 1986; Pile Knapp et al. 2024).

Despite this effectiveness, only 9 out of 249 species (3.6%) showed significant associations with the treatments, and no species was exclusively linked to a single treatment. This limited species-level response indicates resistance to compositional change, likely from the dominance of perennial species and sufficient belowground plant structures, such as buds and rhizomes (Halpern 1988; Klimesˇová and Klimeš 2007; McGlone et al. 2011). Under these conditions, the three-year treatment window and/or disturbance intensity were not enough to substantially influence species-level community composition.

While the overall species-level responses were limited, some notably undesirable forages appeared to be associated with spring browsing, prescribed fire, and their combination. These included white snakeroot (mentioned in the previous discussion) and broomsedge (*Andropogon virginicus* L.). These species likely responded to disturbance in general rather than selective grazing pressure. However, land stewards should remain mindful that selective grazing can influence community composition with sufficient time and grazing pressure (Augustine and McNaughton 1998; Crawley 1983), and monitoring species-level responses is critical for successful land stewardship or silvopasture adoption.

Community stability and resiliency

The abundance of forbs, including the relative proportion of annuals versus perennials, can be influenced by disturbance type and seasonality, with important implications for both production and conservation objectives (Grime 1977; Hobbs and Huenneke 1992). In our study, annual forb coverage remained low and did not differ among treatments, indicating that targeted browsing does not destabilize woodland plant communities (Tilman and Downing 1994).

Floristic metrics provide insight into ecological integrity and resilience. Species richness, mean coefficient of conservatism (mean C), and Floristic Quality Assessment (FQA) integrate diversity with life-history traits and habitat fidelity, allowing assessment beyond abundance alone (Swink and Wilhelm 1979; Taft et al. 1997). Both fire treatments increased richness, a finding which other studies corroborate (Holzmueller et al. 2009; Lettow et al. 2014), indicating that fire is a stronger driver of diversity than browsing in this system. However, mean C values declined significantly under both fire treatments while FQA values remained neutral.

Critically, browsing treatments did not reduce species richness, mean C values, or FQA scores. This challenges the prevailing assumption, embedded in many cost-share programs and management guidelines, that livestock grazing inherently degrades woodland ecological integrity. When properly timed, targeted goat browsing can improve forage composition while maintaining the floristic quality that conservation programs seek to protect.

Study limitations

Several logistical and financial constraints limit the broader applicability of this study. Rotational grazing requires portable electric fencing, which is time-intensive to install and move in woodland settings. Emerging virtual fence technologies, combined with available cost-share programs, may offer a more practical solution for land stewards seeking to implement rotational browsing in woodland settings. Furthermore, grazing at our estimated medium to high stocking density across over 50 acres was conducted by a professional goat contractor. While effective, this approach may not be economically feasible for many private landowners. More realistic scenarios may involve smaller personal herds managed at lower intensity. Our findings may be most applicable to larger landowners or organizations (e.g., land trusts, agencies, or non-profits), with greater capacity for intensive rotational management infrastructure and labor.

Additionally, this study assessed forage composition and cover but not forage yield. For land stewards evaluating economic viability, quantifying forage biomass and nutritional quality under different management regimes remains an important research need. Furthermore, this study represents an initial entry point into woodland-based livestock systems, and future work should explore pathways toward silvopasture grazing enterprises in which producers derive income from livestock production rather than vegetation management services alone. Finally, this study also spanned only three years, a relatively short timeframe for detecting long-term ecological trajectories, and drought conditions in 2022 likely influenced plant community responses.

Management recommendations: goats versus fire

Both targeted browsing and prescribed fire offer viable pathways for managing woodland vegetation, but they produce distinct outcomes. These tradeoffs, summarized in Table 2, illustrate how browsing and fire differentially influence forage production, floristic integrity, and woodland structural outcomes. The choice between these tools should be guided by specific management objectives.

- *For silvopasture and forage production* Spring browsing was most effective, shifting communities toward warm-season grass dominance while maintaining legumes and reducing forbs, and without degrading floristic quality or woodland indicator species. Fall browsing produced more modest effects, trending toward cool-season grasses, which may extend seasonal forage availability.
- *For woodland restoration* Prescribed fire excelled at increasing species richness and woodland indicator species, though diversity gains included ruderal species. The combination of spring browsing and fire increased forage and legumes but was the only treatment negatively associated with white oak and dittany, suggesting compounded distur-

Table 2 Summary of pre-treatment to post-treatment effects on plant functional group and floristic quality metrics relative to control

	Fall browse	Dormant bud + fall browse	Spring browse	Prescribed fire	Spring browse + fire
Community shift[a]	→ CSG	–	↑↑ WSG	↑ Forbs	↑ Forbs
Forage species	–	↓	↑	↑	↑
C4 Grasses	–	–	–	–	–
C3 Grasses	–	–	–	–	–
Legumes	↑	↓	↑	↑	↑↑
Forbs	–	–	–	↑↑	↑↑
Herbs	↑	↓	↑	↑↑	↑↑
Woodies	–	↓	–	↓	–
Indicators	–	↓	↑	↑↑	↑
Annuals	–	↓	–	↑	–
Perennials	↑	↓	↑	↑↑	↑
FQA	–	↓	–	↑	↑
Richness	↑	↓	–	↑↑	↑↑
Mean C	↓	↑	–	↓↓	↓↓
Shannon	↑	↑	↑	–	↑↑

Two arrows indicate a significant difference from control ($p < 0.05$); one arrow indicates a trending difference; dashes indicate no difference. Results are based on post-hoc analysis of univariate linear mixed models

[a]Community shift reflects multivariate trajectory from NMDS ordination (Fig. 4), not univariate testing. Arrows indicate direction of compositional change. WSG = warm-season grass, CSG = cool-season grass. See Results for full ordination analysis

bance may exceed tolerance thresholds for some species valued for restoration and wildlife habitat.

For site renovation The dormant bud + fall browse treatment consistently reduced coverage across nearly all functional groups, which may suit contexts where the goal is suppressing existing vegetation before seeding or planting improved forages.

Conclusion

This study provides evidence that targeted goat browsing can be a viable management tool for balancing the objectives of woodland restoration and silvopasture in the Central Hardwoods Region, though outcomes depend strongly on browse timing and frequency. Across treatments, spring browsing most consistently supported high-quality forage while maintaining floristic quality and woodland indicator species, whereas prescribed fire more strongly promoted restoration outcomes but shifted communities toward greater forb dominance and lower mean conservatism values. Combined browsing and fire produced mixed results, suggesting that compounded disturbances may exceed tolerance thresholds for some species of conservation concern, while repeated browsing regimes generally yielded poor outcomes except where vegetation reduction is desired for site renovation.

Overall, our findings challenge the widespread assumption that livestock grazing and woodland conservation are incompatible. When appropriately timed, targeted goat browsing maintained floristic quality, supported woodland indicator species, and promoted desirable forage composition without the negative ecological consequences often attributed to woodland grazing. These results suggest that silvopasture systems in degraded Central Hardwood woodlands may simultaneously achieve production and conservation objectives, potentially providing land stewards with economic incentives to engage in woodland management that also delivers ecological benefits. Despite their reputation for mischief and chaos, goats may deserve greater recognition as effective stewards of woodland ecosystems when managed appropriately.

Acknowledgements We thank Loren Steele of Living Lands, LLC, for supplying goats and for his valuable contributions to the experimental design of this study. We are grateful to the

Mark Twain National Forest staff, including Kimberly Bittle, Trevor Ozier, Mike Kelly, and Greg Painter, for their expertise and for implementing the prescribed fire treatments. We appreciate the field assistance provided by Texas Nall, Eli Gaffney, Najwa Ghattas, Nathan Waller, and Carlee Steppe. Finally, we thank the associate editor and anonymous reviewers for their constructive feedback on this manuscript.

Author contributions GB contributed to data collection and was a major contributor to the writing of the manuscript. LPK made substantial contributions to the conception, design, analysis, data collection and interpretation, manuscript writing, and acquisition of resources. CC made substantial contributions to data analysis and manuscript writing. DM made substantial contributions to data collection. BD made substantial contributions to the conception, design, data collection, and acquisition of resources. MS made substantial contributions to the conception and design. DD made substantial contributions to the conception, design, and acquisition of resources.

Funding Funding for this work was provided by the United States Department of Agriculture Forest Service, Northern Research Station and the United States Department of Agriculture Forest Service, Mark Twain National Forest. This work was supported by the USDA/ARS, USDA/ARS Dale Bumpers Small Farm Research Center, and University of Missouri Center for Agroforestry under agreement No. 59-6020-5-001**.**

Data availability The datasets generated and analyzed for this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

References

Augustine DJ, McNaughton SJ (1998) Ungulate effects on the functional species composition of plant communities: herbivore selectivity and plant tolerance. J Wildl Manage 62(4):1165–1183. https://doi.org/10.2307/3801981

Bailey DW, Mosley JC, Estell RE, Cibils AF, Horney M, Hendrickson JR, Walker JW, Launchbaugh KL, Burritt EA (2019) Synthesis paper: targeted livestock grazing: prescription for healthy rangelands. Rangeland Ecol Manage 72(6):865–877

Bates D, Mächler M, Bolker B, Walker S (2015) Fitting linear mixed-effects models using lme4. J Stat Softw 67:1–48. https://doi.org/10.18637/jss.v067.i01

Beebe GR (2021). Smoke, goats, and oaks: the effects of targeted goat browsing and prescribed fire on woody regeneration and ground flora in ozark woodlands. University of Missouri.

Beebe GR, Pile Knapp LS, Stambaugh MC, Dey DC, Davidson B, Maddox D, Kabrick JM (2024) Fire versus herbivory for oak woodland restoration: burning achieves short-term structural and compositional objectives whereas browsing alone fails to reduce stem densities and promote ground flora. Fire Ecol 20(1):102. https://doi.org/10.1186/s42408-024-00336-1

Beier RC & Norman JO (1990) The toxic factor in white snakeroot: identity, analysis and prevention. Vet Hum Toxicol 32:81-88.

Briske DD (1993). Strategies of plant survival in grazed systems: A functional interpretation. 37–67.

Briske DD (1996). Strategies of plant survival in grazed systems: a functional interpretation. The Ecol Manag Grazing Syst, 37–67.

Briske DD, Richards JH (1995). Plant responses to defoliation: A physiological, morphological and demographic evaluation. Wildland Plants: Physiol Ecol Dev Morphol, 635–710.

Cáceres MD, Legendre P (2009) Associations between species and groups of sites: indices and statistical inference. Ecology 90(12):3566–3574. https://doi.org/10.1890/08-1823.1

Campbell K, Donlan C (2005) Feral goat eradications on islands. Conserv Biol 19:1362–1374. https://doi.org/10.1111/j.1523-1739.2005.00228.x

Clarke KR (1993) Non-parametric multivariate analyses of changes in community structure. Aust J Ecol 18(1):117–143. https://doi.org/10.1111/j.1442-9993.1993.tb00438.x

Coblentz BE (1978) The effects of feral goats (*Capra hircus*) on island ecosystems. Biol Conserv 13(4):279–286. https://doi.org/10.1016/0006-3207(78)90038-1

Crawley MJ. (1983). Herbivory. The dynamics of animal-plant interactions. Blackwell Scientific Publications

Cubbage F, Balmelli G, Bussoni A, Noellemeyer E, Pachas AN, Fassola H, Colcombet L, Rossner B, Frey G, Dube F, de Silva ML, Stevenson H, Hamilton J, Hubbard W (2012) Comparing silvopastoral systems and prospects in eight regions of the world. Agrofor Syst 86(3):303–314. https://doi.org/10.1007/s10457-012-9482-z

Dey DC, Knapp BO, Battaglia MA, Deal RL, Hart JL, O'Hara KL, Schweitzer CJ, Schuler TM (2019) Barriers to natural regeneration in temperate forests across the USA. New for 50(1):11–40. https://doi.org/10.1007/s11056-018-09694-6

El Aich A, Waterhouse A (1999) Small ruminants in environmental conservation. Small Rumin Res 34(3):271–287. https://doi.org/10.1016/S0921-4488(99)00079-6

Farrington S (2009). Common indicator plants of Missouri Upland Forests (p. 10). Missouri department of conservation.

Fei S, Kong N, Steiner KC, Moser WK, Steiner EB (2011) Change in oak abundance in the eastern United States from 1980 to 2008. For Ecol Manage 262(8):1370–1377. https://doi.org/10.1016/j.foreco.2011.06.030

Fleischner TL (1994) Ecological costs of livestock grazing in Western North America. Conserv Biol 8(3):629–644. https://doi.org/10.1046/j.1523-1739.1994.08030629.x

Frame J, Charlton J, Laidlaw A (1998) Temperate Forage Legumes. CAB Inter. https://doi.org/10.1079/9780851992143.0000

Grime JP (1977) Evidence for the existence of three primary strategies in plants and its relevance to ecological and evolutionary theory. Am Nat 111(982):1169–1194. https://doi.org/10.1086/283244

Halpern CB (1988) Early successional pathways and the resistance and resilience of forest communitie. Ecology 69(6):1703–1715

Hanberry BB, Abrams MD (2018) Recognizing loss of open forest ecosystems by tree densification and land use intensification in the Midwestern USA. Reg Environ Change 18(6):1731–1740. https://doi.org/10.1007/s10113-018-1299-5

Hanberry BB, Dey DC, He HS (2014) The history of widespread decrease in oak dominance exemplified in a grassland–forest landscape. Sci Total Environ 476–477:591–600. https://doi.org/10.1016/j.scitotenv.2014.01.048

Hanberry BB, Nowacki GJ (2016) Oaks were the historical foundation genus of the east-central United States. Quat Sci Rev 145:94–103. https://doi.org/10.1016/j.quascirev.2016.05.037

Hervé M (2024). RVAideMemoire: Testing and Plotting Procedures for Biostatistics (Version R package 0.9-83-7, p. 0.9-83–12) [Computer software]. CRAN. https://CRAN.R-project.org/package=RVAideMemoire

Hester AJ, Edenius L, Buttenschøn RM, Kuiters AT (2000) Interactions between forests and herbivores: the role of controlled grazing experiments. For Inter J for Res 73(4):381–391. https://doi.org/10.1093/forestry/73.4.381

Hobbs RJ, Huenneke LF (1992) Disturbance, diversity, and invasion: implications for conservation. Conserv Biol 6(3):324–337. https://doi.org/10.1046/j.1523-1739.1992.06030324.x

Hodgson J (1990). Grazing management. Science into practice. Longman Scientific & Technical.

Holzmueller EJ, Jose S, Jenkins MA (2009) The response of understory species composition, diversity, and seedling regeneration to repeated burning in Southern Appalachian oak-hickory forests. Nat Areas J 29(3):255–262. https://doi.org/10.3375/043.029.0305

Hutchinson TF, Sutherland EK, Yaussy DA (2005) Effects of repeated prescribed fires on the structure, composition, and regeneration of mixed-oak forests in Ohio. For Ecol Manage 218(1):210–228. https://doi.org/10.1016/j.foreco.2005.07.011

Jose S (2009) Agroforestry for ecosystem services and environmental benefits: an overview. Agrofor Syst 76(1):1–10. https://doi.org/10.1007/s10457-009-9229-7

Karki U, Paneru B, Tiwari A, Ellis N, Bhattrai S, Karki L, Poudel S (2022) Soil quality and growth of southern pines in silvopastures and woodlands integrated with small ruminants. Agrofor Syst 96(3):517–526. https://doi.org/10.1007/s10457-021-00709-4

Khanal PN, Grebner DL, Munn IA, Grado SC, Grala RK, Henderson JE (2017) Evaluating non-industrial private forest landowner willingness to manage for forest carbon sequestration in the southern United States. For Policy Econ 75:112–119. https://doi.org/10.1016/j.forpol.2016.07.004

Kinkead CO, Kabrick, JM, Stambaugh MC, Grabner KW (2013). Changes to oak woodland stand structure and ground flora composition caused by thinning and burning. Proceedings, 18th Central Hardwood Forest Conference; 2012 March 26-28; Morgantown, WV., 117, 373–383

Klimešová J, Klimeš L (2007) Bud banks and their role in vegetative regeneration – a literature review and proposal for simple classification and assessment. Perspect Plant Ecol Evol Syst 8(3):115–129. https://doi.org/10.1016/j.ppees.2006.10.002

Knapp BO, Stephan K, Hubbart JA (2015) Structure and composition of an oak-hickory forest after over 60 years of repeated prescribed burning in Missouri, U.S.A. For Ecol Manage 344:95–109. https://doi.org/10.1016/j.foreco.2015.02.009

Kuznetsova A, Brockhoff PB, Christensen RHB (2017) lmerTest package: tests in linear mixed effects models. J Stat Softw 82:1–26. https://doi.org/10.18637/jss.v082.i13

Ladd D, Thomas JR (2015) Ecological checklist of the Missouri flora for floristic quality assessment. Phytoneuron 12(1):1–274

Launchbaugh KL, Walker J (2006). Targeted grazing: A new paradigm for livestock management. Targeted Grazing: A natural approach to vegetation management and landscape enhancement, 2–8.

Lenth RV (2023). Emmeans: Estimated marginal means, aka least-squares means. (Version R package version 1.8.9) [Computer software]. https://cran.r-project.org/package=emmeans

Lettow MC, Brudvig LA, Bahlai CA, Landis DA (2014) Oak savanna management strategies and their differential effects on vegetative structure, understory light, and flowering forbs. For Ecol Manage 329:89–98. https://doi.org/10.1016/j.foreco.2014.06.019

Lovreglio R, Meddour-Sahar O, Leone V (2014) Goat grazing as a wildfire prevention tool: a basic review. Iforest Biogeosci for 7(4):260. https://doi.org/10.3832/ifor1112-007

MacFarland K, Feibel S, Batcheler M, Moore A, Smith MM, Joslin A (2025) Silvopasture: an agroforestry practice. USDA for Serv. https://doi.org/10.2737/NAC-AN-8

Mancilla-Leyton JM, Martin Vicente A (2012) Biological fire prevention method: Evaluating the effects of goat grazing on the fire-prone mediterranean scrub. For Syst. https://doi.org/10.5424/FS/2012212-02289

Manousidis T, Kyriazopoulos AP, Parissi ZM, Abraham EM, Korakis G, Abas Z (2016) Grazing behavior, forage selection and diet composition of goats in a Mediterranean woody rangeland. Small Rumin Res 145:142–153. https://doi.org/10.1016/j.smallrumres.2016.11.007

McGlone CM, Sieg CH, Kolb TE (2011) Invasion resistance and persistence: established plants win, even with disturbance and high propagule pressure. Biol Invasions 13(2):291–304. https://doi.org/10.1007/s10530-010-9806-8

McNaughton SJ (1979) Grazing as an optimization process: grass-ungulate relationships in the Serengeti. Am Nat 113(5):691–703. https://doi.org/10.1086/283426

National oceanic and atmospheric administration. (2022). *2022 Annual Climate Summary*. NOAA's National weather service. https://www.weather.gov/sgf/news_climate_2022_year_end_summary

National Research Council (2007) Nutrient requirements of small ruminants: sheep, goats, cervids, and New World Camelids. National Academies Press, Washington, DC

Nuzzo VA (1986) Extent and status of Midwest oak savanna: presettlement and 1985. Nat Areas J 6(2):6–36

Oksanen J, Simpson GL, Blanchet FG, Kindt R, Legendre P, Minchin PR, O'Hara RB, Solymos P, Stevens MHH, Szoecs E, Wagner H, Barbour M, Bedward M, Bolker B, Borcard D, Borman T, Carvalho G, Chirico M, Caceres MD, Weedon J (2022). vegan: Community Ecology Package (Version 2.7–2) [Computer software]. https://cran.r-project.org/web/packages/vegan/index.html

Oswalt SN, Smith WB, Miles PD., Pugh SA (2014). Forest Resources of the United States, 2012: A technical document supporting the Forest Service 2010 update of the RPA Assessment. Gen. Tech. Rep. WO-91. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office. 218 p., 91. https://doi.org/10.2737/WO-GTR-91

Pierce RA, Kallenbach R, Reinbott T, Wright R, Udawatta R (2017). Mixtures of native warm-season grasses, forbs and legumes for biomass, forage and wildlife habitat. University of Missouri Extension. https://extension.missouri.edu/media/wysiwyg/Extensiondata/Pub/pdf/agguides/wildlife/g09423.pdf

Pile Knapp LS, Dey DC, Stambaugh MC, Thompson FR, Varner JM (2024) Managing forward while looking back: reopening closed forests to open woodlands and savannas. Fire Ecol 20(1):72. https://doi.org/10.1186/s42408-024-00312-9

R Core Team. (2024). R*:* A language and environment for statistical computing (Version 4.5.0) [Computer software]. R Found Stat Comput.

Reid JL, Holmberg NJ, Albrecht M, Arango-Caro S, Hajek O, Long Q, Trager J (2020) Annual understory plant recovery dynamics in a temperate woodland mosaic during a decade of ecological restoration. Nat Areas J 40(1):23–34. https://doi.org/10.3375/043.040.0104

Rosa García R, Celaya R, García U, Osoro K (2012) Goat grazing, its interactions with other herbivores and biodiversity conservation issues. Small Rumin Res 107(2):49–64. https://doi.org/10.1016/j.smallrumres.2012.03.021

Shifley SR, Moser WK, Nowak DJ, Miles PD, Butler BJ, Aguilar FX, DeSantis RD, Greenfield EJ (2014) Five anthropogenic factors that will radically alter forest conditions and management needs in the Northern United States. For Sci 60(5):914–925. https://doi.org/10.5849/forsci.13-153

Swink F, Wilhelm G. (with The Morton Arboretum). (1979). Plants of the Chicago Region 3rd edn. http://archive.org/details/plantsofchicagor0000floy

Taft J, Wilhelm GS, Ladd DM, Masters LA (1997) Floristic quality assessment for vegetation in Illinois, a method for assessing vegetation integrity. Erigenia 15:3–95

Tilman D, Downing J (1994) Biodiversity and stability in grasslands. Nature 367:363–365. https://doi.org/10.1038/367363a0

Torralba M, Fagerholm N, Burgess PJ, Moreno G, Plieninger T (2016) Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis. Agric Ecosyst Environ 230:150–161. https://doi.org/10.1016/j.agee.2016.06.002

Tsiouvaras CN, Havlik NA, Bartolome JW (1989) Effects of goats on understory vegetation and fire hazard reduction in a coastal forest in California. For Sci 35(4):1125–1131. https://doi.org/10.1093/forestscience/35.4.1125

Úbeda X, Alcañiz M, Borges G, Outeiro L, Francos M, Úbeda X, Alcañiz M, Borges G, Outeiro L, Francos M (2019) Soil quality of abandoned agricultural terraces managed with prescribed fires and livestock in the Municipality of Capafonts, Catalonia, Spain (2000–2017). Agronomy. https://doi.org/10.3390/agronomy9060340

U.S. National Integrated Drought Information System. (n.d.). Historical Information. https://www.drought.gov/historical-information

USDA. (2022). State Agriculture Overview for Missouri. https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=MISSOURI&year=2022

University of Missouri Extension. (n.d.). Dairy Grazing: Growth of pasture plants. https://extension.missouri.edu/publications/m182

Valderrábano J, Torrano L (2000) The potential for using goats to control *Genista scorpius* shrubs in European black pine stands. For Ecol Manage 126(3):377–383. https://doi.org/10.1016/S0378-1127(99)00108-5

Webster CR, Dickinson YL, Burton JI, Frelich LE, Jenkins MA, Kern CC, Raymond P, Saunders MR, Walters MB, Willis JL (2018) Promoting and maintaining diversity in contemporary hardwood forests: confronting contemporary drivers of change and the loss of ecological memory. For Ecol Manage 421:98–108. https://doi.org/10.1016/j.foreco.2018.01.010

Wickham H. (2016). ggplot2: Elegant graphics for data analysis. Springer-Verlag. https://doi.org/10.1007/978-3-319-24277-4