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Oak regeneration under varying treatment regimes: management guidelines and implications for at-risk avian species

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Oak Regeneration Under Varying Treatment Regimes: Management Guidelines and Implications for At-risk Avian Species

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Abstract

Lack of regeneration has been documented in a wide variety of oak species across the globe, leading to widespread conversion of oak forests. This lack of oak recruitment has severe consequences for wildlife species that depend on oak forests, including numerous federally listed threatened/endangered species found on military lands. The golden-cheeked warbler (*Setophaga chrysoparia*) is one such species, dependent on oak forests for breeding but experiencing habitat loss throughout its range, including on Fort Hood, Texas. The majority of studies that have examined mechanisms behind oak recruitment failure have occurred in the Eastern and Western United States, with relatively little work in the oak-juniper forests of central Texas where the warbler occurs. In particular, little is known about how military land management practices influence oak recruitment and, therefore, long-term maintenance of oak habitats. The objectives of this project were to 1) conduct a review of current literature on oak recruitment failure and best management practices to facilitate oak regeneration and 2) empirically evaluate the effects of forest management practices on oak recruitment in oak-juniper habitats, with a focus on military land management.

Current literature on the topic of oak recruitment is extensive but overall trends are emerging. Numerous studies from the Eastern United States have identified lack of disturbance (i.e., wildfire and logging) and associated proliferation of shade tolerant species as primary mechanisms for lack of oak recruitment. In the oak forests of the Western United States, the effects of herbivores on oak recruitment, including small mammals and cattle, has been well documented. Work in the central US is sparser but would suggest that similar factors are at play, including fire suppression and deer herbivory.

We conducted habitat assessments on sites with varying treatment regimes at Fort Hood, Texas to quantify impacts on oak recruitment. Treatments included mechanically thinned with slash applied as mulch, mechanically thinned with slash removed, wildfire, and unmanaged (control). Within these plots, we assessed ground cover, herbivore browse, and stem density of all seedlings, shrubs, saplings and trees. We also categorized use of plots by herbivores using game cameras and herbivore sign. We documented very little seedling recruitment on plots that had experienced mechanical thinning, particularly those where mulch was present. Seedling recruitment was significantly higher in unmanaged and wildfire sites. We also documented extensive use of thinned plots by herbivores, particularly white-tailed deer and domestic cattle, as well as high levels of browsed stems.

In combination, our results suggest that oak recruitment on military lands will require a combination of management strategies. When mechanical thinning is required in oak habitats, secondary management strategies such as prescribed fire, herbivore control and/or shrub management is recommended to facilitate oak recruitment. Although not a planned activity, wildfire appears to encourage oak recruitment, although herbivore control may be necessary in areas with high herbivore densities. Management strategies to increase oak recruitment can benefit a wide variety of at-risk wildlife species on military installations, thereby meeting natural resource management objectives and compliance with the Endangered Species Act.

Introduction

Numerous North American oak species are experiencing recruitment failure (Aldrich et al. 2005) with a variety of mechanisms proposed (MacDougall et al. 2010), including long-term fire suppression (Abrams and Nowacki 1992, Shumway et al. 2001), land use change (Abrams 2003), and herbivory (e.g. Tyler et al. 2002). This lack of oak recruitment is an emerging threat to many at-risk wildlife populations that depend on oak forests (McShea and Healy 2002), including a large number of threatened/endangered species managed on military lands. In particular, the golden-cheeked warbler (*Setophaga chrysoparia,* Figure 1) is a federally listed endangered migratory bird species that breeds exclusively in Central Texas, including large breeding populations on Fort Hood, Texas.

Figure 1. Golden-cheeked Warbler on Fort Hood, Texas. Photo credit: Gil Eckrich.

Golden-cheeked warbler population declines are largely thought to be a function of loss of the mature oak-juniper woodlands on which the species depends, with urban expansion, oak wilt and wildfire all contributing factors (Groce et al. 2010). Loss of habitat due to urban expansion is typically considered permanent whereas loss to wildfire temporary. However, recovery of forests after wildfire can take decades to become viable golden-cheeked warbler habitat, if ever. Loss of oak recruitment, including due to fire suppression and browsing by ungulates (Russel and Fowler 1999; Groce et al. 2010), can greatly slow or impede oak forest regeneration. A number of forest management strategies are currently employed to create or maintain warbler habitat, but it is unknown how these strategies influence oak recruitment and, thereby, long-term maintenance of warbler habitat.

Figure 2. Shin Oak (Quercus sinuata) seedling emerging from mulch following mechanical thinning on Fort Hood, Texas.

Forest management strategies across the breeding range of golden-cheeked warblers (and the recently delisted black-capped vireo; *Vireo atricapilla*) includes mechanical thinning and prescribed burning (Reidy et al. 2016). The combination of these strategies can maintain habitat structures known to be important for avian species while reducing risk of catastrophic wildfire. Following thinning, the resulting slash is often either mulched in place (Figure 2) or combined into piles. The effects of thinning and prescribed burning on oak recruitment have been examined in a variety of systems (reviewed in Brose et al. 2013), with these methods showing varying success in increasing oak recruitment. However, the vast majority of work has focused on eastern hardwood forests (Brose et al. 2013) or southwestern oak species (e.g. Tyler et al. 2006), with relatively little work conducted in the oak-juniper woodlands that comprise golden-cheeked warbler habitat. A recent study in oak-juniper woodlands in Texas found that fire and browsing can influence oak regeneration but that longer term studies are needed (Andruk et al. 2014). Further, there is very little known about the effects of secondary forest management practices (e.g. slash application) on oak recruitment. In fact, the only work on the subject has focused on the positive effects of mulch on planted oak seedling survival (Devine et al. 2007) but no empirical data is available on widespread mulch application effects on seed germination and sprouting. Maintenance of golden-cheeked warbler habitat on military lands, and thus maintenance of the species, requires a better understanding of the impacts of military land management on oak recruitment.

Project Objective

The objectives of our study were to 1) conduct a review of current literature on oak recruitment failure and best management practices to facilitate oak regeneration and 2) empirically evaluate the effects of forest management practices on oak recruitment in oak-juniper habitats with a focus on military land management. Fort Hood military reservation provides a unique opportunity to examine this question as Fort Hood has conducted forest management over many decades, creating a patchwork of treatments of various ages, facilitating long-term and short-term analyses. In addition, Fort Hood is home to the endangered golden-cheeked warbler, whose habitat requirements include oak. The results here are broadly relevant to oak recruitment on military lands and specifically applicable to golden-cheeked warbler habitat management on Fort Hood.

Methods

Literature Review

For our first objective, we conducted a literature review of current information on oak recruitment that would be relevant to DoD natural resource managers. To facilitate direct relevance to specific DoD installations, we divided our review into studies taking place in three broad geographic regions – the Western, Eastern and Central US. Although the issue of oak recruitment spans all geographic areas, the different oak species, as well as climate and herbivore community, differ enough among regions that we felt a regional approach would be valuable. We focused specifically on studies that examined either mechanisms behind recruitment failure or management strategies that influence oak regeneration. Although not comprehensive, this review is meant to provide a general summary of the state of oak recruitment understanding in the US.

Oak Recruitment on Fort Hood

For our second objective, we evaluated oak recruitment in woodland plots that had experienced mechanical thinning, wildfire or unmanaged (control) at Fort Hood, Texas. Fort Hood is a 88,557 ha installation in Bell and Coryell Counties, Texas. Fort Hood vegetation consists primarily of perennial grasslands and shrubland/forest, predominantly composed of Ashe Juniper (*Juniperus ashei*), live oak (*Quercus fusiformis*), shin oak (*Quercus sinuate*) and Texas red oak (*Quercus buckleyi).*

We identified forest patches that had previously been either mechanically thinned with slash removed, mechanically thinned with slash mulched in place, and/or experienced wildfire. We similarly identified nearby control sites that had not experienced any recent management or disturbance. All thinning efforts occurred 2–3 years prior to habitat measurements and wildfire sites had experienced wildfires that occurred in either 1996 or 2008.

Habitat assessments were based on methods detailed in Reemts and Hansen (2008). We randomly established transects in each forest patch, as identified above. Transects were 110 m long and followed either a random bearing (for level sites) or were perpendicular to the slope (i.e., followed contour lines). Plots were located at 10 m intervals along the right side of the transects and 7 of the 11 possible plots were randomly selected for sampling. Within each 10 x 10 m plot, we nested 5 x 5 m and 1 x 1 m plots (Figure 3). We visually inspected each plot for fecal evidence of cattle, deer, rabbit or feral hog, as well as evidence of hog rooting.

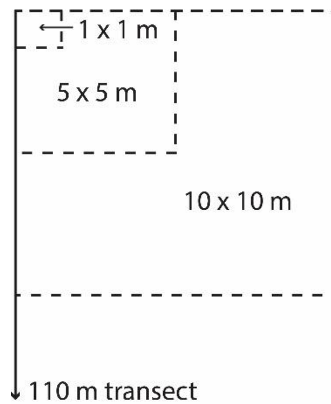

Figure 3. Schematic of habitat assessment plots at Fort Hood, Texas.

Within the 1 x 1 m plot, we visually assessed percentage ground cover of the following categories: woody debris, herbaceous cover, grass cover, leaf litter, succulent cover, bare ground and mulch cover. We also calculated canopy cover via densiometer from the 1 m^2 quadrat.

Within the 5 x 5 m plot, we estimated stem density of all seedlings (<0.3 m tall), shrubs (between 0.3-1.8 m tall) and saplings (>1.8 m tall and <5 cm diameter at breast height [dbh]). For multi-stemmed shrubs, stems that split above the root crown were counted as one. Saplings were divided into five dbh classes: 0–0.9, 1.0–1.9, 2.0–2.9, 3.0–3.9 and 4.0–4.9 cm. For multi-stemmed individuals, only the largest stem was measured and counted.

Within the 10 x 10 m plot, we estimated tree (>5 cm dbh) density. If the trunk branched above the root crown, only the largest stem was measured and counted. Species was documented for all stems and trees.

Figure 4. Habitat assessments transect on plot that had been mechanically thinned and slash applied as mulch at Fort Hood, Texas.

At a subset of sites, we deployed game cameras to monitor mammalian use of the plots. A total of 17 cameras were deployed at randomly selected sites within thinned patches. For 2020, cameras were deployed on 23 July and retrieved on 25 September. We used Bushnell Trophy cameras, placed approximately 0.3 m off the ground. We compared mammalian densities in thinned sites compared to current and previously collected game camera data in unmanaged sites (control). For these sites, we used Reconyx PC800 Hyperfire, XP9 Ultrafire and HC600 Hyperfire (Reconyx, Holmen, Wisconsin, USA) set up in a grid of 20 cameras placed 500 m apart (Avrin et al. 2021). Grids were left in place for an average of 39 trap nights and then moved to the next grid. Data was collected 13 November 2018 to 17 April 2019 and from 19 December 2019 to 13 May 2020.

Statistical Methods

To assess whether probability of detecting cattle, deer, and feral hog sign differed between management treatments (thinned, wildfire, or control), we used generalized linear mixed models (GLMM) assuming a binomial distribution. We used linear mixed models (LMM) to determine if microhabitat variables (percentage of woody debris, grass, herbaceous vegetation, etc.) in 1 x 1 m plots differed between treatment and control plots. To evaluate whether the number of stems, seedlings, shrubs, and saplings of all plant species differed between management treatments, we used GLMMs assuming a Poisson distribution. We used LMMs to determine whether dbh of all plant species differed between management treatments; again, we included the number of mature trees per plot as an additive fixed effect in these models. We replicated analyses for stems, seedlings, shrubs, saplings, and dbh and for each oak (*Quercus*) species, and we also compared the number of seedlings per management treatment for all *Quercus* species combined. We further explored how the number of seedlings per plot was affected by specific thinning practices by considering thinned and mulched and only thinned plots as separate treatments. To control for the often-repeated measurements of plots on each transect, we nested plot ID within transect ID as a random effect in all the above models. Mixed models were run using the lme4 package (Bates et al. 2015) in R version 3.6 (R Core Team 2020). We used negative binomial generalized linear models in R to explore whether the total number of camera trap detections for each animal species differed between thinned and control plots. We generated predicted (estimated marginal) means with 95% confidence intervals (CI) for all response variables using the emmeans package (Lenth 2020).

Results

Literature Review

Western United States

A large number of studies focused on western US oak species have found that herbivory is largely responsible for oak recruitment failure. A large experimental study in California found that herbivory and seed predation, primarily by small mammals, significantly reduced oak survival (Tyler et al. 2002). MacDougall et al (2010) experimentally examined recruitment in *Quercus garryana* and found that herbivory by small mammals (mostly non-native) resulted in nearly total recruitment failure. Similarly, McLaughlin and Zavaleta (2013) found that moisture stress and small mammal herbivory affected recruitment of *Quercus lobata*. Recruitment of *Quercus douglasii* was shown to be influenced by climate and herbivory, primarily small mammals and cattle (Borchert et al. 1989). Perea et al. (2017) also found that deciduous oak species were heavily impacted by herbivory but that browse pressure was reduced in areas of high shrub cover. Although most studies have focused on small mammal browse, experimental evidence in rangelands suggests that cattle herbivory and trampling can have a strong negative impact on oak survival (Hall et al. 1992; López-Sánchez et al. 2014).

Eastern United States

In the eastern United States, much previous work has focused on the influence of fire suppression and land use change on oak regeneration. Analyses of historic logging and fire regimes suggest that lack of fire in the last century has resulted in increase of later successional species (*Acer* and *Prunus*) and reduction in oak recruitment (Abrams and Nowacki 1992; Shumway et al. 2001). Abrams (2003) conducted a review of the historic and current state of white oak (*Quercus alba*) in the eastern united states and concluded that the decline in white oak (and subsequent increase in red oak) is likely a result of lack of fire and logging, leading to increase in more competitive, shade-tolerant species. Experimental applications of prescribed fire and mechanical thinning found that oak were outcompeted by early-successional species and so it is recommended that prescribed fire be applied several years following mechanical thinning to control resprouting of other, fast-growing species (Albrecht and McCarthy 2006). In addition to historic land use change, work in eastern Canada has also demonstrated the negative impacts of (primarily invasive) grasses on oak seedling growth (Natvik and Henry 2021)

Central United States

In comparison to the eastern and western regions, relatively little work has been done addressing oak recruitment in the central US. Long-term study of forest composition in Indiana found that logging and fire suppression since 1917 has resulted in a shift to shade tolerant species and lack of oak recruitment (Aldrich et al. 2005). Similarly, long-term monitoring of oak stands in Arkansas suggest declines in oak species due to reduced disturbance (primarily fire) regime (Chapman et al. 2006). In Texas, evidence suggests a combination of deer browse and fire suppression leading to lack of oak recruitment over the last century (Russel and Fowler 2002; Andruk et al. 2014).

International Studies

Several studies have demonstrated the importance of shrub cover for reducing herbivory for European oak species (e.g., Perea et al. 2020, Smit et al. 2008). Rolo et al. (2012) found that oak recruitment could be experimentally increased with the presence of shrub cover by improving microclimate and providing protection from predators. Similarly, Smit et al. (2012) found that presence of coarse woody debris can increase oak recruitment, largely through protection of acorns and seedlings from predators. Wild boar herbivory was shown to impact recruitment rate and spatial distribution of oak in Spain (Gómez and Hódar 2008).

Reviews

Dey (2014) conducted a review of the current state of oak management in the US and provided suggestions for future management. Given the lack of recruitment in unmanaged stands and the conversion to shade-tolerant species, Dey (2014) suggests that oak are now management dependent and that shelterwood timber harvesting in combination with prescribed fire has shown the most promise for oak recruitment.

Pulido et al. (2013) provide a review of oak regeneration challenges in Europe and California (largely included above), followed by a suite of management suggestions; these include livestock exclusion, weed control, small mammal exclusion (e.g., cages or fencing) and use of shrub cover or woody debris for seedling shelters (Pulido et al. 2013).

Oak Recruitment on Fort Hood

Habitat Assessments

We conducted habitat assessments at 175 plots that had been mechanically thinned with mulch application, 49 plots that had been mechanically thinned and slash removed, 455 plots that had experienced wildfire and 308 unmanaged (control) plots. The probability of detecting cattle feces was significantly higher in thinned sites compared to control (P <

0.001) or wildfire (P < 0.001) sites, whereas the probability of detecting deer feces was similar in thinned and control plots (P = 0.95) and reduced in wildfire sites (both P < 0.01; Figure 5). The probability of detecting feral hog feces was similar among sites (all P > 0.14) but the probably of detecting rooting was higher in thinned plots compared to control (P = 0.01) or wildfire plots (P < 0.01; Figure 5, Appendix A).

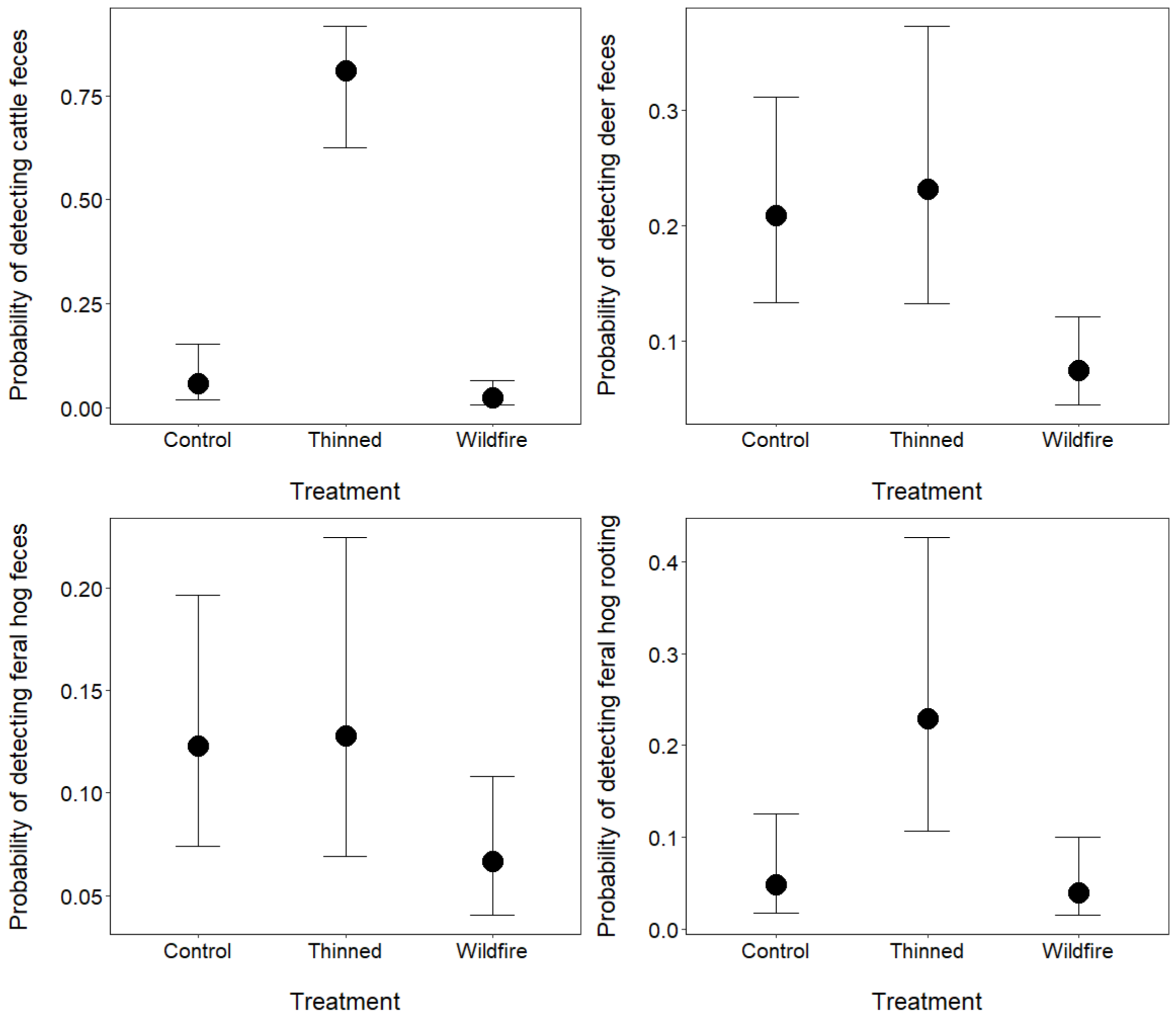

Figure 5. Mean (± 95% CI) probability of detecting cattle, deer, and feral hog sign at control (unmanaged), mechanically thinned, and wildfire plots at Fort Hood, Texas.

The number of stems browsed was significantly higher in thinned sites compared to control ($P < 0.001$) or wildfire ($P = 0.03$; Figure 6). There was marginally higher browse in wildfire compared to control plots ($P = 0.05$). More browsed stems were detected in thinned vs. control plots for red oak (*Quercus buckleyi*), live oak (*Quercus fusiformis*), and shin oak (*Quercus sinuata*) (all $P < 0.01$), whereas the number of browsed post oak (*Quercus stellata*) stems did not differ between management treatments (all $P > 0.99$).

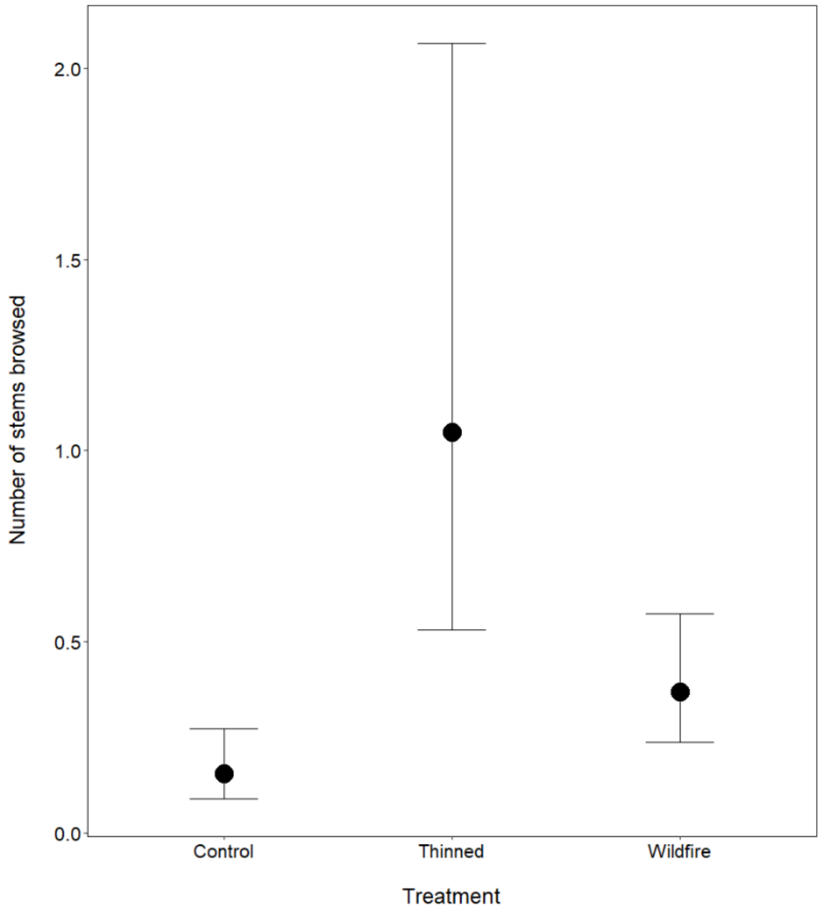

Figure 6. Mean (±95% CI) number of stems browsed in control (unmanaged), mechanically thinned and wildfire plots at Fort Hood, Texas.

Within the 1 x 1 m plots, herbaceous and grass cover was higher in thinned plots compared to wildfire ($P < 0.01$ and $P = 0.143$) or control plots (both $P < 0.01$), whereas woody debris cover, leaf litter, and woody vegetation cover were all lower on thinned plots compared to wildfire (all $P < 0.001$) or control (all $P < 0.001$; Figure 7). Non-zero data were too sparse to model mulch and succulent cover.

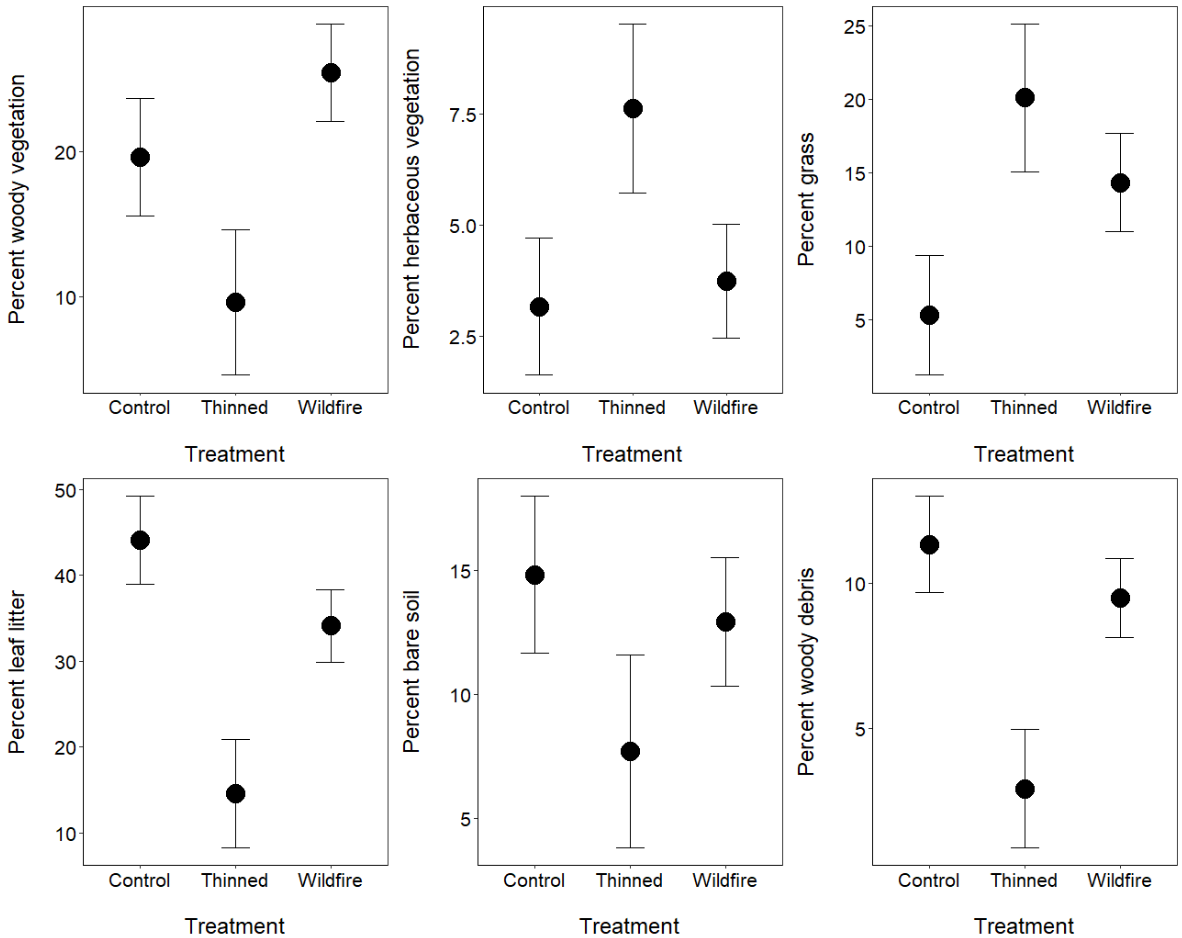

Figure 7. Mean (±95% CI) ground cover estimates in control (unmanaged), mechanically thinned, and wildfire plots at Fort Hood, Texas.

The average number of seedlings present per plot was greatly reduced on thinned plots compared to wildfire ($P < 0.001$) or control ($P < 0.001$; Figure 8). When considering all *Quercus* species together, thinned plots had a lower average number of seedlings compared to control and wildfire plots (both $P < 0.01$), the latter of which did not differ ($P = 0.64$). Sample sizes for individual oak species was small but non-significant trends are similar for red oak and shin oak whereas abundances were similar among treatments for live oak and post oak. When separating thinning treatments by thinned and mulched and thinned only, thinned only plots had fewer seedlings than thinned and mulched plots ($P < 0.001$), but both thinning treatments had fewer seedlings than control and wildfire plots (both $P < 0.01$).

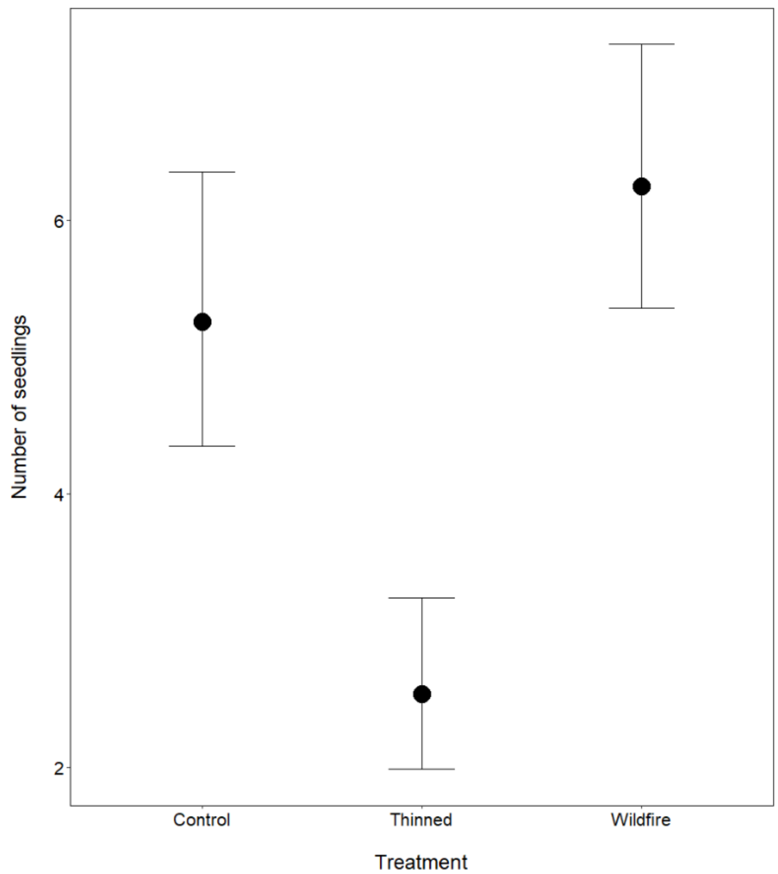

Figure 8. Mean (±95% CI) number of seedlings in control (unmanaged), mechanically thinned and wildfire plots at Fort Hood, Texas.

Abundances of shrubs and saplings was highest on wildfire sites followed by control and then thinned (Figure 9). When considering each *Quercus* species separately, red oak shrubs tended to be more abundant on control than thinned or wildfire plots (both $P < 0.07$), live oak shrubs tended to be more abundant on wildfire compared to control ($P = 0.02$) and thinned plots ($P = 0.08$), whereas shrub counts did not differ between management treatments for shin or post oak (all $P > 0.4$). The only notable differences we detected for saplings of each *Quercus* species were that live oak saplings tended to be more abundant on wildfire than control plots ($P = 0.06$), and shin oak saplings were more abundant on wildfire vs. thinned plots ($P < 0.01$).

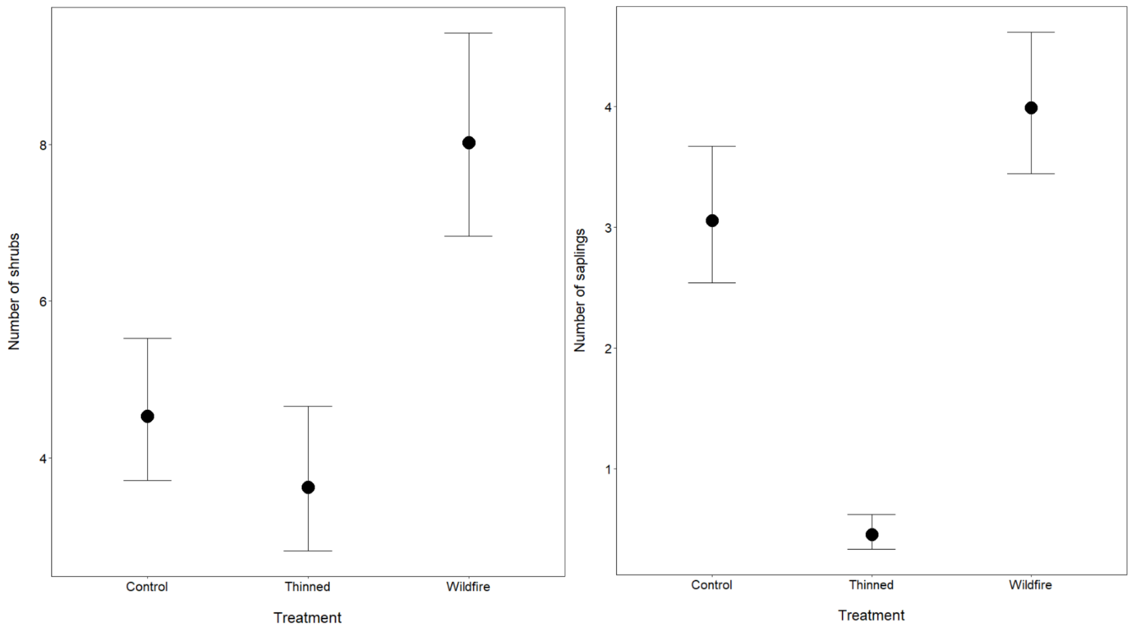

Figure 9. Mean (± 95% CI) of shrubs and saplings in control (unmanaged), mechanically thinned and wildfire plots at Fort Hood, Texas.

Average size (DBH) of trees per site was significantly higher on thinned sites than control or wildfire ($P < 0.001$), reflecting the selective removal of smaller trees.

Game Cameras

We include data here from 257 cameras representing 9,888 trap nights in control (unmanaged) sites and 17 cameras representing 756 trap nights in thinned plots. We did not have any cameras in wildfire sites. Mean number of cow detections per trap night was much higher in thinned compared to control plots (0.29 ± 0.73 and 0.05 ± 0.27, respectively; $z = 13.62$, $P < 0.001$; Figure 10). White-tailed deer detections were also higher in thinned compared to control sites (0.47 ± 0.78 and 0.11 ± 0.36, respectively; $z = 19.82$, $P < 0.001$; Figure 10). In contrast, feral hog and lagomorph (eastern cottontail and jackrabbit) were higher in control compared to thinned plots (hog = 0.10 ± 0.35 and 0.01 ± 0.13, $z = -6.25$, $P < 0.001$; lagomorph = 0.24 ± 0.63 and 0.03 ± 0.22, $z = -9.407$, $P < 0.001$).

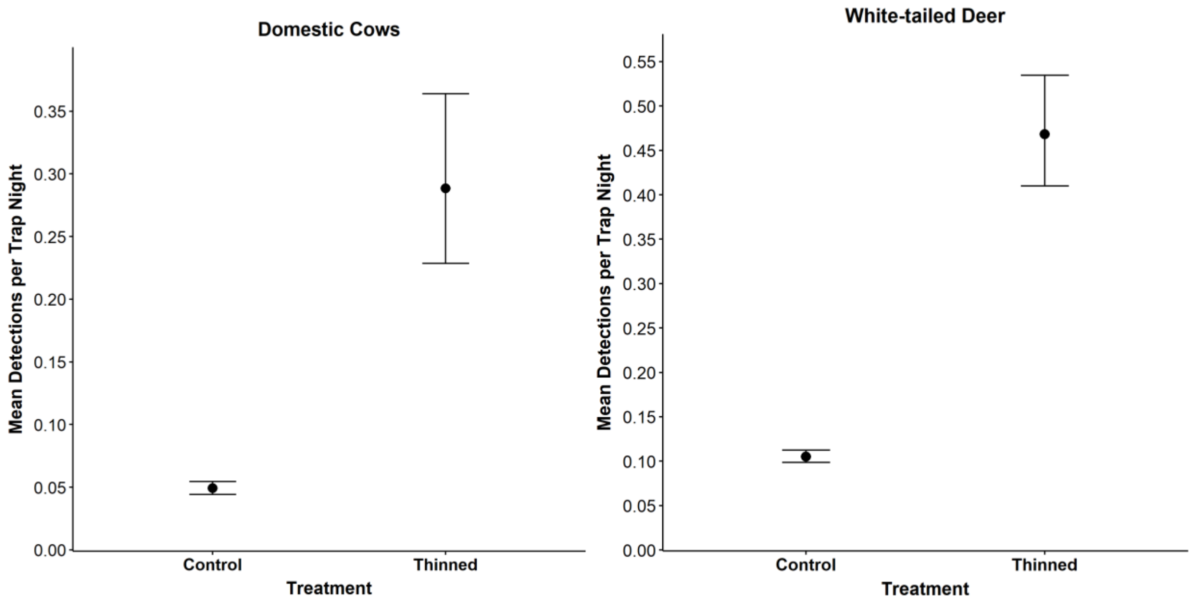

Figure 10. Mean (± 95% CI) detections per trap night of domestic cattle and white-tailed deer at control (unmanaged) and mechanically thinned plots Fort Hood, Texas.

Game camera images show heavy and extended use of thinned sites by cattle (Figures 11 and 12). Herds of cattle would not only move through the sites but would spend long periods of time (3+ hours) foraging and resting.

Figure 11. Game camera images of cattle foraging in mechanically thinned plots on Fort Hood, Texas.

Figure 12. Game camera images of cattle utilizing mechanically thinned plots for extensive (3+ hour) periods on Fort Hood, Texas.

Discussion

A review of literature on oak regeneration found that studies in the eastern US tend to focus on lack of disturbance (i.e., wildfire and logging) and associated proliferation of shade tolerant species as the primary mechanisms for lack of oak recruitment (e.g., Abrams and Nowacki 1992, Shumway et al. 2001, Dey 2014). Studies in the western US have largely focused on the negative impacts of herbivory on oak recruitment, to include both small mammals (e.g., MacDougall et al. 2010) and cattle (e.g., Hall et al. 1992). There have been relatively few studies in the central US, although studies in the Midwest demonstrate similar findings to eastern US studies with lack of disturbance driving oak recruitment failure (e.g., Aldrich et al. 2005, Chapman et al. 2006). In Texas, where this study was conducted, the small number of studies completed have implicated fire suppression and deer herbivory as primary mechanisms behind declining oak populations (Russel and Fowler 2002, Andruk et al. 2014).

We documented reduced densities of seedlings on mechanically thinned compared to unmanaged (control) or wildfire sites. This was true across all plant species as well as specifically for oak species. Although all thinned plots had reduced densities of seedlings, sites where the resultant slash was mulched in place and spread on the ground had particularly low levels of recruitment. We are not aware of any other studies that evaluated the effects of widespread mulch application for oak recruitment, but our results would suggest that removal or burning of slash would be preferable for oak recruitment. In addition to seedlings, we also documented reduced densities of shrubs and saplings on mechanically thinned compared to wildfire or control plots. However, the reduced number of saplings (and possibly shrubs) is likely largely due to the thinning prescription. Because the thinning only took place two years prior to habitat assessments, recruitment following thinning would largely be limited to seedlings and some fast-growing shrubs.

We found heavy use of mechanically thinned sites by ungulates, particularly cattle and white-tailed deer. This was evident both in the fecal surveys and game camera traps. The game camera images showed extensive use of the thinned sites by cattle including foraging and long periods (3+ hours) of continuous use. Not surprisingly given the extensive use of thinned plots by ungulates, we documented higher numbers of browsed stems on the thinned plots. In combination, these results suggest that use of thinned sites by cattle and deer can reduce plant restoration potential through browse and trampling. Interestingly, we found that feral hog and rabbit detections were higher in control sites than thinned sites. However, we found relatively low levels of browse in control sites, suggesting that they are not foraging extensively in those sites. We did note more evidence of hog rooting in thinned compared to control plots, suggesting that hogs are foraging at least occasionally in the thinned areas. Previous work has demonstrated negative impacts of feral hogs on oak regeneration (Gómez and Hódar 2008, Siemann et al. 2009) but we are not able to parse the relative impacts of each herbivore species in our study.

Our results suggest that mechanical thinning without any herbivory control or prescribed burn results in very low levels of oak recruitment. Numerous studies have documented the importance of herbivore control for oak recruitment (e.g., Leonarsson et al. 2015), including the need for rotational cattle grazing strategies that reduce browse pressure (Hall et al. 1992). Most studies addressing cattle herbivory on oak species were focused on California rangelands (e.g., Hall et al. 1992, López-Sánchez et al. 2014). We are not able to find any previous similar work in mixed hardwood forested habitats, but our results would suggest that cattle extensively utilize thinned plots for foraging and resting. This is likely because the thinning opens up pathways for movement and facilitates growth of the herbaceous layer, as demonstrated in our herbaceous cover results. In contrast to wild mammals documented using the thinned sites, cattle spent long periods of time at the sites, often observed laying and resting. This behavior likely has negative implications for oak regeneration including browse pressure and trampling.

Mechanical thinning of forested plots on Fort Hood rarely incorporates prescribed burning, likely due to potential for fire spread into adjoining forested habitats. As such, most prescribed burning on Fort Hood takes place in more open, savannah habitats. Previous work in Alabama demonstrated the importance of prescribed burning on oak recruitment in forested sites with no documented recruitment in sites that had been heavily thinned without associated burning (Schweitzer et al. 2019). Our results support this previous work, suggesting that heavy thinning without prescribed fire results in very low levels of oak recruitment, at least in the short-term. All of the sites on Fort Hood were heavily thinned, however, Schweitzer et al. (2019) found that light thinning without fire resulted in low levels of oak recruitment suggesting that, if prescribed burning is not possible, that lighter thinning would be preferable for oak recruitment.

Although our study plots that had experienced wildfire were much more advanced than our thinned sites (the fires occurred in 1996 and 2008), the 1996 wildfire sites had been repeatedly monitored since the fire (Reemts and Hansen 2008). This previous work suggests that oak densities recovered relatively quickly after the fire (Reemts and Hansen 2008) and our current work demonstrates a near complete recovery with oak numbers similar in the wildfire and control (unburned) sites. Unfortunately, we do not have herbivory browse data in the years after the fire, but the proliferation of oak seedlings soon after the fire (Reemts and Hansen 2008) would suggest relatively low browse pressure. There could be several factors at play including lower densities of cattle in these areas. Most cattle grazing on Fort Hood occurs on western Fort Hood where there are more extensive savannah habitats. The wildfires occurred in eastern Fort Hood, which is more heavily forested, resulting in the wildfire sites being further from areas of higher density cattle grazing and, thus, may have reduced use of cattle. Further, feral hog populations in Texas have been generally increasing over the last several decades (Mapston 2007) which would suggest that hog densities may have been lower immediately after the fires occurred. We would recommend monitoring of any future wildfires in forested habitat to understand use of wildfire sites by domestic cattle and feral hogs.

Management Implications

The results of our study, in combination with a literature review of the current state of knowledge, suggest that oak regeneration on military installations will likely require a suite of management strategies. Although mechanical thinning of forested habitats is often required to increase line-of-sight for military exercises, we would recommend either subsequent prescribed burning of the thinned plots (Dey 2014) or a lighter thinning prescription (Schweitzer et al. 2019), if oak recruitment is a desired outcome. Although not relevant to all installations, our results suggest that cattle use of thinned sites and associated browse pressure has negative effects on oak recruitment. If possible, rotational grazing or cattle management (e.g., fencing) may be required in thinned sites, at least until oak sapling are large enough to avoid heavy browse pressure and trampling risk. Several recent studies have found that presence of shrub cover (Perea et al. 2020, Smit et al. 2008, Rolo et al. 2012) and/or course woody debris (Smit et al. 2012) can increase oak recruitment by reducing oak predation and creating favorable microclimates. Planting or maintenance of shrub and/or wood debris cover on thinned plots may therefore increase oak recruitment following management.

Although not a planned land management activity, wildfires are common on many DoD installations due to the fire potential of military training activities, such as artillery. Our results indicate relatively high levels of oak recruitment in areas that have experienced wildfire, suggesting that wildfire on military installations may aid in long-term oak regeneration. We did not document herbivore use of wildfire plots but herbivory control (e.g., fencing) may be necessary in areas of high herbivore densities.

Many wildlife species, including the endangered golden-cheeked warbler, are dependent on oak habitat (Kroll 1980, McShea and Healy 2002). In central Texas, the amount of golden-cheeked warbler habitat has been decreasing over time, largely due to development and, on Fort Hood, wildfire (Groce et al. 2010). Although loss of habitat to wildfire is typically considered temporary, lack of oak recruitment following fire can result in permanent habitat loss. Our results suggest that oak recruitment is relatively high in sites that had experienced wildfire but that herbivory control may be necessary. Our results also highlight the importance of oak recruitment strategies, particularly herbivore management, when conducting forest thinning in avian habitat.

Military Mission Benefits

Understanding the impacts of military land management on oak recruitment is critical for DoD land managers when developing appropriate forest management programs on installations that harbor at-risk and endangered wildlife species that are dependent on oak habitats. Maintenance of habitat for at-risk avian species helps to ensure that installations are in compliance with the Migratory Bird Treaty Act, Endangered Species Act, and Sikes Act. The results of this project are relevant not only to the host installation, Fort Hood, but also any installation that provides breeding habitat for at-risk wildlife species associated with oak habitats, including the Air Force managed Joint Base San Antonio–Camp Bullis that also provides habitat for the endangered golden-cheeked warbler. Beyond the range of the golden-cheeked warbler in central Texas, a large number of installations employ forest management strategies and the information garnered from this project inform the conservation of wildlife habitat while maintaining habitats for military training and testing.

Literature Cited

Abrams, M.D., 2003. Where Has All the White Oak Gone? BioScience 53, 927. https://doi.org/10.1641/0006-3568

Abrams, M.D., Nowacki, G.J., 1992. Historical Variation in Fire, Oak Recruitment, and Post-Logging Accelerated Succession in Central Pennsylvania. Bulletin of the Torrey Botanical Club 119, 19. https://doi.org/10.2307/2996916

Albrecht, M.A., McCarthy, B.C., 2006. Effects of prescribed fire and thinning on tree recruitment patterns in central hardwood forests. Forest Ecology and Management 226, 88–103. https://doi.org/10.1016/j.foreco.2005.12.061

Aldrich, P.R., Parker, G.R., Romero-Severson, J., Michler, C.H., 2005. Confirmation of oak recruitment failure in Indiana old-growth forest: 75 years of data. Forest Science 51, 406–416.

Andruk, C.M., Schwope, C., Fowler, N.L., 2014. The joint effects of fire and herbivory on hardwood regeneration in central Texas woodlands. Forest Ecology and Management 334, 193–200. https://doi.org/10.1016/j.foreco.2014.08.037

Avrin, A.C., Pekins, C.E., Sperry, J.H., Allen, M.L., 2021. Evaluating the efficacy and decay of lures for improving carnivore detections with camera traps. Ecosphere 12. https://doi.org/10.1002/ecs2.3710

Bates, D. Maechler, M. Bolker, B., Walker, S. 2015. Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software 67, 1–48.

Borchert, M.I., Davis, F.W., Michaelsen, J., Oyler, L.D., 1989. Interactions of Factors Affecting Seedling Recruitment of Blue Oak (Quercus Douglasii) in California. Ecology 70, 389–404. https://doi.org/10.2307/1937544

Chapman, R.A., Heitzman, E., Shelton, M.G., 2006. Long-term changes in forest structure and species composition of an upland oak forest in Arkansas. Forest Ecology and Management 236, 85–92. https://doi.org/10.1016/j.foreco.2006.08.341

Dey, D.C., 2014. Sustaining Oak Forests in Eastern North America: Regeneration and Recruitment, the Pillars of Sustainability. Forest Science 60, 926–942. https://doi.org/10.5849/forsci.13-114

Gómez, J.M., Hódar, J.A., 2008. Wild boars (Sus scrofa) affect the recruitment rate and spatial distribution of holm oak (Quercus ilex). Forest Ecology and Management 256, 1384–1389. https://doi.org/10.1016/j.foreco.2008.06.045

Hall, L.M., George, M.R., McCreary, D.D., Adams, T.E., 1992. Effects of cattle grazing on blue oak seedling damage and survival. Journal of Range Management 503–506.

Kroll, J.C. 1980. Habitat requirements of the golden-cheeked warbler: management implications. Journal of Range Management 33, 60-65.

Lenth, R. 2020. emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.5.1. https://CRAN.R-project.org/package=emmeans.

Leonardsson, J., Löf, M., Götmark, F., 2015. Exclosures can favour natural regeneration of oak after conservation-oriented thinning in mixed forests in Sweden: A 10-year study. Forest Ecology and Management 354, 1–9. https://doi.org/10.1016/j.foreco.2015.07.004

López-Sánchez, A., Schroeder, J., Roig, S., Sobral, M., Dirzo, R., 2014. Effects of Cattle Management on Oak Regeneration in Northern Californian Mediterranean Oak Woodlands. PLoS ONE 9, e105472. https://doi.org/10.1371/journal.pone.0105472

MacDougall, A.S., Duwyn, A., Jones, N.T., 2010. Consumer-based limitations drive oak recruitment failure. Ecology 91, 2092–2099. https://doi.org/10.1890/09-0204.1

Mapston, M., 2007. Feral Hogs in Texas. Texas Wildlife Services.

McLaughlin, B.C., Zavaleta, E.S., 2013. Shifting bottom-up and top-down regulation of oak recruitment across a regional resource gradient: Shifting bottom-up and top-down regulation. Global Ecology and Biogeography 22, 718–727. https://doi.org/10.1111/geb.12028

Natvik, M., Henry, H.A.L., 2021a. Implications of common ancestral habitat of grass cover for oak recruitment: Differential effects of Festuca rubra and two native grasses. Forest Ecology and Management 495, 119350. https://doi.org/10.1016/j.foreco.2021.119350

Perea, R., López-Sánchez, A., Dirzo, R., 2017. Differential tree recruitment in California oak savannas: Are evergreen oaks replacing deciduous oaks? Forest Ecology and Management 399, 1–8. https://doi.org/10.1016/j.foreco.2017.05.018

Perea, R., López-Sánchez, A., Pallarés, J., Gordaliza, G.G., González-Doncel, I., Gil, L., Rodríguez-Calcerrada, J., 2020. Tree recruitment in a drought- and herbivory-stressed oak-beech forest: Implications for future species coexistence. Forest Ecology and Management 477, 118489. https://doi.org/10.1016/j.foreco.2020.118489

Pulido, F., McCreary, D., Cañellas, I., McClaran, M., Plieninger, T., 2013. Oak Regeneration: Ecological Dynamics and Restoration Techniques, in: Campos, P., Huntsinger, L., Oviedo Pro, J.L., Starrs, P.F., Diaz, M., Standiford, R.B., Montero, G. (Eds.), Mediterranean Oak Woodland Working Landscapes. Springer Netherlands, Dordrecht, pp. 123–144. https://doi.org/10.1007/978-94-007-6707-2_5

R Core Team. 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Reemts, C.M., Hansen, L.L., 2008. Slow recolonization of burned oak-juniper woodlands by Ashe juniper (Juniperus ashei): Ten years of succession after crown fire. Forest Ecology and Management 255, 1057-1066.

Rolo, V., Plieninger, T., Moreno, G., 2013. Facilitation of holm oak recruitment through two contrasted shrubs species in Mediterranean grazed woodlands. J Veg Sci 24, 344–355. https://doi.org/10.1111/j.1654-1103.2012.01458.x

Russell, F.L., Fowler, N.L., 2002. Failure of adult recruitment in Quercus buckleyi populations on the Eastern Edwards Plateau, Texas. American Midland Naturalist 148, 201–217.

Schweitzer, C.J., Dey, D.C., Wang, Y., 2019. White Oak (Quercus alba) Response to Thinning and Prescribed Fire in Northcentral Alabama Mixed Pine–Hardwood Forests. Forest Science 65, 758–766. https://doi.org/10.1093/forsci/fxz031

Shumway, D.L., Abrams, M.D., Ruffner, C.M., 2001. A 400-year history of fire and oak recruitment in an old-growth oak forest in western Maryland, U.S.A. Canadian Journal of Forest Research 31, 1437–1443. https://doi.org/10.1139/x01-079

Siemann, E., Carrillo, J.A., Gabler, C.A., Zipp, R., Rogers, W.E., 2009. Experimental test of the impacts of feral hogs on forest dynamics and processes in the southeastern US. Forest Ecology and Management 258, 546–553. https://doi.org/10.1016/j.foreco.2009.03.056

Smit, C., Kuijper, D.P.J., Prentice, D., Wassen, M.J., Cromsigt, J.P.G.M., 2012. Coarse woody debris facilitates oak recruitment in Białowieża Primeval Forest, Poland. Forest Ecology and Management 284, 133–141. https://doi.org/10.1016/j.foreco.2012.07.052

Smit, C., Ouden, J., Díaz, M., 2008. Facilitation of *Quercus ilex* recruitment by shrubs in Mediterranean open woodlands. Journal of Vegetation Science 19, 193–200. https://doi.org/10.3170/2007-8-18352

Tyler, C.M., Mahall, B.E., Davis, F.W., Hall, M., 2002. Factors limiting recruitment in valley and coast live oak. Proceedings of the Fifth Symposium on Oak Woodlands: Oaks in California's Challenging Landscape. Gen. Tech Rep. PSW-GTR-184, Albany, CA: Pacific Southwest Research Station, Forest Service, U.S. Department of Agriculture 565–572.

Appendices

Appendix A: Tables of Tukey contrasts showing estimated mean differences, standard errors (SE), and P-values for Control, Thinned, and Wildfire plots on Fort Hood, Texas.

Probability of detecting animal feces and feral hog rooting			
Linear hypothesis	Estimate	SE	P-value
Cattle feces			
Thinned - Control	4.2277	0.8265	<0.001
Wildfire - Control	-0.9423	0.5117	0.151
Wildfire - Thinned	-5.1700	0.8453	<0.001
Deer feces			
Thinned - Control	0.1327	0.4357	0.94995
Wildfire - Control	-1.1873	0.3711	0.00391
Wildfire - Thinned	-1.3200	0.4292	0.00597
Feral hog feces			
Thinned - Control	0.04393	0.43126	0.994
Wildfire - Control	-0.67679	0.36090	0.145

Wildfire - Thinned	-0.72072	0.41653	0.193
Feral hog rooting			
Thinned - Control	1.7601	0.6238	0.0131
Wildfire - Control	-0.2126	0.5107	0.9084
Wildfire - Thinned	-1.9727	0.6022	0.0029

Microhabitat			
Linear hypothesis	Estimate	SE	P-value
Woody vegetation			
Thinned - Control	-9.992	3.245	0.00574
Wildfire - Control	5.795	2.650	0.07259
Wildfire - Thinned	15.787	3.030	<0.001
Herbaceous vegetation			
Thinned - Control	4.4635	1.2451	0.00102
Wildfire - Control	0.5728	1.0170	0.83870
Wildfire - Thinned	-3.8907	1.1627	0.00247
Grass			
Thinned - Control	14.787	3.277	<0.001
Wildfire - Control	9.032	2.675	0.002
Wildfire - Thinned	-5.755	3.059	0.143
Leaf litter			
Thinned - Control	-29.548	4.103	<0.001
Wildfire - Control	-9.968	3.349	0.00795
Wildfire - Thinned	19.580	3.831	<0.001
Bare soil			
Thinned - Control	-7.133	2.533	0.0132
Wildfire - Control	-1.909	2.068	0.6237
Wildfire - Thinned	5.224	2.365	0.0690
Woody debris			
Thinned - Control	-8.419	1.325	<0.001
Wildfire - Control	-1.850	1.082	0.2
Wildfire - Thinned	6.569	1.237	<0.001

Stems			
Linear hypothesis	Estimate	SE	P-value
All species			
Thinned - Control	1.9096	0.4480	<0.001
Wildfire - Control	0.8633	0.3628	0.0451
Wildfire - Thinned	-1.0463	0.4123	0.0296
Red oak (*Quercus buckleyi*)*			
Thinned - Control	5.812	1.244	<0.001

Live oak (*Quercus fusiformis*)			
Thinned - Control	4.7594	1.7347	0.01680
Wildfire - Control	-0.8816	1.4810	0.82205
Wildfire - Thinned	-5.6410	1.7015	0.00265
Shin oak (*Quercus sinuata*)			
Thinned - Control	5.736	1.445	0.000207
Wildfire - Control	-1.607	1.326	0.444564
Wildfire - Thinned	-7.343	1.581	<0.001
Post oak (*Quercus stellata*)			
Thinned - Control	0.1066	3.0586	0.999
Wildfire - Control	-0.1498	2.5601	0.998
Wildfire - Thinned	-0.2564	2.3343	0.993

Seedlings			
Linear hypothesis	Estimate	SE	P-value
All species			
Thinned - Control	-0.7297	0.1616	<0.001
Wildfire - Control	0.1726	0.1259	0.353
Wildfire - Thinned	0.9022	0.1460	<0.001
Red oak (*Quercus buckleyi*)			
Thinned - Control	-0.6165	0.4471	0.348
Wildfire - Control	0.2044	0.3202	0.796
Wildfire - Thinned	0.8209	0.4282	0.131
Live oak (*Quercus fusiformis*)			
Thinned - Control	0.5457	0.5038	0.521
Wildfire - Control	0.4187	0.3859	0.520
Wildfire - Thinned	-0.1270	0.4420	0.955
Shin oak (*Quercus sinuata*)			
Thinned - Control	-0.4652	0.3699	0.412
Wildfire - Control	-0.1529	0.2413	0.798
Wildfire - Thinned	0.3123	0.3459	0.633
Post oak (*Quercus stellata*)			
Thinned - Control	0.18427	0.61988	0.951
Wildfire - Control	0.27659	0.48900	0.835
Wildfire - Thinned	0.09232	0.48122	0.979
All *Quercus* species			
Thinned - Control	-1.0675	0.2788	<0.001
Wildfire - Control	-0.1814	0.2038	0.64286
Wildfire - Thinned	0.8862	0.2562	0.00171

All species with Thin/Mulch			
Thin/Mulch - Control	-0.4586	0.1494	0.00931
Thinned - Control	-2.8370	0.3806	<0.001
Wildfire - Control	0.1710	0.1117	0.38972
Thinned - Thin/Mulch	-2.3784	0.3860	<0.001
Wildfire - Thin/Mulch	0.6297	0.1349	<0.001
Wildfire - Thinned	3.0081	0.3759	<0.001

Shrubs			
Linear hypothesis	Estimate	SE	P-value
All species			
Thinned - Control	-0.2231	0.1670	0.372
Wildfire - Control	0.5697	0.1316	<0.001
Wildfire - Thinned	0.7928	0.1502	<0.001
Red oak (*Quercus buckleyi*)			
Thinned - Control	-1.1422	0.5111	0.0635
Wildfire - Control	-0.7885	0.3447	0.0560
Wildfire - Thinned	0.3538	0.4822	0.7394
Live oak (*Quercus fusiformis*)			
Thinned - Control	0.1176	0.4607	0.9640
Wildfire - Control	0.9350	0.3421	0.0169
Wildfire - Thinned	0.8174	0.3808	0.0785
Shin oak (*Quercus sinuata*)			
Thinned - Control	-0.5500	0.4692	0.463
Wildfire - Control	-0.3833	0.3032	0.408
Wildfire - Thinned	0.1667	0.4417	0.923
Post oak (*Quercus stellata*)			
Thinned - Control	0.93376	0.78943	0.461
Wildfire - Control	-0.03698	0.61285	0.998
Wildfire - Thinned	-0.97074	0.75944	0.405

Saplings			
Linear hypothesis	Estimate	SE	P-value
All species			
Thinned - Control	-1.8945	0.1832	<0.001
Wildfire - Control	0.2663	0.1199	0.0654
Wildfire - Thinned	2.1609	0.1727	<0.001
Red oak (*Quercus buckleyi*)			
Thinned - Control	-0.5565	0.6952	0.686
Wildfire - Control	0.2697	0.2333	0.457
Wildfire - Thinned	0.8262	0.6821	0.424
Live oak (*Quercus fusiformis*)			

Thinned - Control	0.3909	0.5355	0.7361
Wildfire - Control	0.6363	0.2829	0.0587
Wildfire - Thinned	0.2454	0.4841	0.8624
Shin oak (*Quercus sinuata*)			
Thinned - Control	-0.7143	0.3842	0.14143
Wildfire - Control	0.3895	0.1847	0.08175
Wildfire - Thinned	1.1038	0.3728	0.00764
Post oak (*Quercus stellata*)+			
Wildfire - Control	-0.7375	0.4789	0.124

DBH			
Linear hypothesis	Estimate	SE	P-value
All species			
Thinned - Control	18.282	2.296	<0.001
Wildfire - Control	-6.641	1.814	0.000765
Wildfire - Thinned	-24.923	2.128	<0.001
Red oak (*Quercus buckleyi*)			
Thinned - Control	24.998	2.352	<0.001
Wildfire - Control	-3.459	1.591	0.0731
Wildfire - Thinned	-28.457	2.089	<0.001
Live oak (*Quercus fusiformis*)			
Thinned - Control	31.933	7.812	0.000119
Wildfire - Control	-11.965	6.504	0.155580
Wildfire - Thinned	-43.897	6.963	<0.001
Shin oak (*Quercus sinuata*)			
Thinned - Control	1.3283	0.9226	0.31674
Wildfire - Control	-1.9939	0.6932	0.01097
Wildfire - Thinned	-3.3222	0.9391	0.00112
Post oak (*Quercus stellata*)			
Thinned - Control	0.9284	2.7344	0.937460
Wildfire - Control	-9.2731	2.3654	0.000258
Wildfire - Thinned	10.2014	2.0339	<0.001

*Adequate wildfire treatment data were not available for analysis.

+Adequate thinning treatment data were not available for analysis.