Effects of prescribed burning and thinning on oak regeneration in northeast Kansas

by

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Abstract

Mature oak woodlands are being converted to shade-tolerant lower value species in the eastern United States, and several studies indicate that the situation started after fire suppression policies were implemented. This study was conducted on a 90-acre tract of oak-dominated woodland near Manhattan, Kansas. The study aimed to assess the effectiveness of burning and thinning to encourage oak regeneration. The experimental design was 2 (Burn) x 2 (Thin) factorial in a repeated measures design. The resulting treatment combinations were burn and thin (BT), burn and no-thin (BNT), no-burn and thin (NBT), and no-burn and no-thin (NBNT – control). The burning and thinning operations were conducted in the Spring 2015 and Spring 2018. Vegetation inventories were conducted on permanent plots before burning in 2014, Fall 2016, and Fall 2018 to assess the effects of the treatments on vegetation composition and fuel loading. The thinning treatment reduced the total number of trees per acre after the second thinning operation. The burning and thinning combined treatments significantly reduced the basal area of the primary competitor species. While the number of oak saplings per acre is not different from the main competitors in thinned plots, main competitors outnumbered oak saplings in no-thin plots, and burning significantly reduced the total number of saplings per acre. The burn in 2018 also significantly reduced the total number of seedlings per acre. However, burn and thin treatments did not affect the seedlings species composition, and eastern redbud outnumbered oaks in 2018 averaged across all treatments. Fuel loading was measured pre- and post-burning, in 2015 and 2018, using both nondestructive (sampling plane or transect) and destructive (quadrat) methods, to evaluate fuel consumption and recovery. Overall, both methods showed the same trends for the fuels; however, the quadrat method was more conservative. There was a significant recovery of litter fuel load from 2015 to 2018 and a significant decrease from pre- to post-burning in 2018 of

the litter and duff layer. The quadrat method presented an interaction between time and thin. Total fuel load consumption was significant only in 2018 and 1000-hr sound fuel was the only fuel affected by thinning.

Table of Contents

List of Figures

List of Tables

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Dedication

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Chapter 1 - Literature Review

Historical development of the eastern oak forests

Oaks (*Quercus spp.*) occur throughout the United States, as solitary individuals, a few scattered trees, significant portions of complex, mixed-species assemblages, and nearly pure monocultures (Brose et al., 2014). Approximately 10,000 years B.P., at the end of last ice age, most of the eastern United States was occupied by oak forests (Abrams, 1992). Moreover, paleoecological evidence indicates temporal co-occurrence of oaks and fire (Abrams, 1992, Abrams, 2016, Arthur et al., 2012).

Native Americans of the Central Plains used fires to create oak savannahs and manage tallgrass prairies to enhance forage for large herbivores, and later the suppression of these fires led to the conversion of the savannahs and tallgrass prairies to closed oak forests (Abrams, 2016). The dating of fire scars on old-growth trees shows that periodic fire (every 5-25 years) was common in eastern United States oak woodlands (Abrams, 2016). Stambaugh, Guyette & Marschall (2003) developed a fire history for northeastern Oklahoma on lands previously occupied by the Cherokee Nation, which suggested that the fire frequency was more strongly associated with human population density than with drought events. Native Americans may have been more responsible for the fires that maintained the ecosystem than naturally occurring fires.

After European settlement, there were clearcutting events followed by wildfires; however, the species composition of eastern forests changed very little (Abrams, 2016). The suppression of forest fires that started in the 1930s (“Smokey Bear” era) resulted in dramatic changes in structure and composition of the forests, impeding oak species regeneration and resulting in their replacement by shade-tolerant species (Abrams, 2016).

The eastern part of Kansas is included in the Oak Savannahs and Prairie Region, a transitional area between the forests of the Eastern United States and the grasslands of the Great Plains (Oswalt & Olson, 2016). Most of the land in this region is privately owned, and includes some of the most productive agricultural lands in the country, with forested areas limited to riparian zones, steep slopes and scattered savannahs (Johnson et al., 2002). As a result of 20th century fire suppression policies, forests encroached upon grassland. However, the invading species were American elm (*Ulmus Americana)*, hackberry (*Celtis occidentalis*) and eastern redcedar (*Juniperus virginiana*) rather than oaks (Johnson et al., 2002).

The Value of Oak Ecosystems

Oaks are important to wildlife and to the economy. Oak species are some of the most valuable timber species in eastern hardwood forests, and when oak is replaced by less valuable species, it may affect negatively the landowners' income (Burhans et al., 2016). All the activities related to the oak wood processing industry generates jobs in North America (Brose et al. 2014).

Oak woodlands provide the habitat for insects and vertebrates, and acorns and leaves are consumed by many species (Brose et al., 2014, Burhans et al., 2016). Acorns are consumed by black bears, white-tailed deer, small mammals, eastern wild turkey, ruffed grouse and other birds (Fearer, 2016). Oak leaves are consumed by native lepidopteran species and white-tailed deer, the leaves are used as an insulation layer in squirrels' and other small mammals' nests during the winter and the uneven canopy provides preferred nesting habitat for many birds (Brose et al., 2014, Fearer, 2016).

Reintroducing fire into the forests

Positive effects

Fire is a natural ecological process that has been influencing forests dynamics for millennia. The occurrence of fires is important to oak ecology because it prepares a proper seedbed, increases sunlight to the forest floor, and suppresses undesirable competitive species. The change in species dominance as a result of fire suppression can affect biodiversity, wildlife population densities, timber production, forest hydrology, nutrient cycling, and fuel loading (Nowacki & Abrams, 2008).

Periodic prescribed fire can be used for ecological restoration as a process to restore the structure and function of an ecosystem (Brose et al., 2014). Fire contributes to the landscape heterogeneity, creating vegetation mosaics of burned and unburned areas (Miller & Urban, 1998). The suppression of fire can lead to disappearance of some plant species, creating altered forest composition and structure (Harper & Keyser, 2016).

Early fall fires that occur before acorn drop can help oak seedling establishment (Brose et al., 2013) because fire reduces the density of competing species and destroys their seeds stored in the litter. Furthermore, fires eliminate physical barriers to seedling establishment by reducing the thickness of the litter layer and degrading habitats for animals and fungi that feed on acorns (Brose et al., 2014).

Besides aiding with regeneration, fire can also reduce oak diseases. Withgott (2004) discovered that sudden oak death (SOD), a disease caused by a fungus, was much less prevalent in areas that were burned. Older trees, more prevalent in unburned stands, are less resistant to pathogens. Trees stressed by competition will produce fewer defensive chemicals (Withgott, 2004).

Negative effects

Fires that occur in late fall and early winter, after seed drop and leaf fall, remove the protective covering offered by the current year's leaves, which can result in seed desiccation over the winter, and the heat from a fire soon after acorn drop can kill a high proportion of the seeds (Dey & Fan, 2009).

Fires can kill trees by girdling the base of the tree, or completely scorching or burning through the crown. Girdling will often top-kill oaks and other resprouting hardwoods but will completely kill species unable to sprout from belowground (e.g. eastern redcedar) (Frelich et al, 2015).

One problem caused by burning is that fire scars reduce timber value, which may be a concern for landowners. Due to this risk of damage, prescribed fire is not recommended on highly productive sites unless timber value is not a consideration (Harper & Keyser, 2016). The use of fire is recommended if the primary objective is to improve wildlife habitat.

Oaks readily resprout following fire, but it is not known if prescribed fire increases rates of germination, seedling establishment, or the growth of advanced regeneration (Andruk et al., 2014).

Prescribed fire as a silvicultural practice to restore oak ecosystems

Mature oak (*Quercus* spp.) woodlands are being converted to shade-tolerant species throughout the eastern United States. Dendrochronological studies suggest oak regeneration problems began after the implementation of fire suppression (Arthur et al., 2012). Most upland oak species have physiological and morphological adaptations to periodic fire and drought, such as moderately high light requirements, strong resprouting capacity, and thick bark (Abrams, 1992, Arthur et al., 2012), which provide advantages compared to other competing species. Fan et al. (2012) observed that ten years of repeated burning reduced stem density by 57% under fully-stocked oak-hickory forests. Oaks mortality rates ranged from 28 to 54%.

Considering the evidence that fire has a role in oak regeneration, the fire-oak hypothesis was developed, which consists of four parts (Brose et al., 2014): (1) Fire historically has been essential to upland oak ecosystems maintenance in eastern North America, (2) Oaks are better adapted to survive and regenerate after periodic fire compared to other hardwoods, (3) The suppression of periodic fire in the early 1900s is the main cause for the existing oak regeneration problem, and (4) Prescribed fire has the potential to help oak regeneration in some situations.

Regeneration Response

Acorns have hypogeal germination, meaning that the germination takes place below the ground and the cotyledons remain non-photosynthetic, which can help to protect the cotyledons against the fire. Oaks seedlings develop a large root system and store carbohydrates in their root tissues (Brose et al., 2014), which allows them to survive after being top-killed following a low-intensity fire (Fox & Creighton, 2016). In an unburned environment, oak seedlings, with a root-centric growth pattern, are often outcompeted by species with a shoot-centric growth because the later grow faster and shade out oaks (Stringer, 2016).

Oaks are excellent sprouters (Brose et al., 2014); thus, they can sprout with relative ease after burnings. According to Dey and Hartman (2005), the ability to sprout post-fire increases exponentially as basal diameter increases. However, young and small seedlings more readily die because their roots have not developed sufficient energy reserves.

Fire can change the regeneration pool of seedlings by heat-induced mortality or combustion, seedbed preparation for new seedlings, and stimulation of the sprouting response of fire-damaged or top-killed plants; thus, it is important to consider the fire effects on competing species at the seedling establishment stage (Arthur et al., 2012).

Oak seedlings can survive in a partially shaded environment through a slow growth rates. However, if low light levels persist, they eventually die (Stringer, 2016). A disturbance is necessary to make oak seedlings more competitive. Even if the understory light environment is improved with prescribed fire, this does not mean that an oak seedling will be able to effectively respond because the seedlings must be relatively large (basal diameter of more than 0.65 in. [1.9cm]) before burning to resprout vigorously and be competitive after a fire (Arthur et al., 2012). When oak seedlings and sprouts are small and are growing in dense understory shade, they develop small root systems with few root carbohydrate reserves and cannot resprout post-fire (Brose, 2014). Having 100-200, 4-feet tall seedlings per acre can successfully ensure oak regeneration (Stringer, 2016).

Superior oak sprouting after fire was not universally observed in previous research. When conducting growing-season burns, higher oak sprouting rates than their competitors were frequently observed. However, some growing-season burns resulted in a post-fire oak sprouting rate that was less than the rate for other species. For most dormant-season burns, the post-fire sprouting rate of oaks was not significantly higher than those of the competing species (Dey, 2014).

Brose (2014) states that prescribed fire can be used in mature oak stands with little or no oak reproduction to help start the regeneration process; however, Stringer (2016) reports that a proper oak reproduction prior to the treatment is necessary. The study conducted by Fan et al. (2012) concluded that reproduction of oaks and hickories was relatively favored by repeated, low-intensity fires compared to other tree species, indicating they have potential to persist in forests where periodic fires are conducted, typical of woodland restoration projects.

Site quality and fire intensity

Site quality is related to the site timber productivity. Oak regeneration is more common on low-quality sites because fast growing mesic species are less adapted to those sites. The leaf area of stands in high-quality sites is higher, which decreases light infiltration, and increases the number and growth rate of competing species (Stringer, 2016).

Regulations for conducting prescribed fires encourage the use of low-intensity fires because of safety concerns, as well as logistical and infrastructure limitations, and often results in unsuccessful long-lasting increases in the understory light necessary for oak development (Arthur et al., 2012).

Smith and Sutherland (1999) concluded in their study that oaks wounded by low-intensity fires are capable of compartmentalizing fire scars effectively, limiting the spread of decay and contributing to tree survival. The oaks' response after a low-intensity fire is important because mature oak stands are at the beginning of the regeneration process, and most later successional species have low resistance to fire (Abrams, 1992). If oaks are not regenerated at this time, the site will be occupied by other species.

Fire frequency

According to Arthur et al. (2012), continuous studies are necessary to assess the consequences of long-term and frequent fire use on biodiversity, species invasions, air and water pollution, soil fertility, and potential interactions with climate change. It is also important to understand the ecological and social tradeoffs of the use of fires. According to Brose et al. (2014), when the burning frequency is higher than recommended, there is not enough time for the species to recover their physiological functions before next burn. Multiple burns enhance understory light levels, repeatedly kill competitive species and allow oaks to re-sprout vigorously. However, with repeated top-kill and re-sprouting, oak root stocks will diminish overtime (Galgamuwa, 2017).

Previous studies found that the number of oak seedlings decreased or did not change substantially following a single dormant-season fire; two prescribed fires showed varying responses, with positive and negative outcomes, and multiple prescribed fires generally resulted in positive effects on oak regeneration (Brose et al., 2014). Fewer studies were done with growing-season burns, and they presented positive and negative outcomes for oak regeneration after a single fire (Brose et al., 2014). According to Brose (2014), prescribed fires conducted in mid- to late- April do not favor seedling regeneration because small seedlings may have already begun utilizing their root carbohydrate reserves.

Fire historically occurred every 25 years in oak woodlands of the eastern United States, and every 4-6 years in many sites, and a common recommendation is to burn savannahs every 2-4 years (Harper & Keyser, 2016). A study conducted by Abrams (1985) in the Konza Prairie Research Natural Area, in Manhattan, Kansas, concluded that historical fire frequency in the region was between the calculated mean fire interval (MFI) documented by tree fire scars (11-20 years) and the MFI for Flint Hills prairie fires (2-3 years).

Thinning

Thinning is a forestry technique that mimics the natural process of mortality in forests, redistributing growth to remaining trees on the site and increasing light infiltration (Clatterbuck, 2016). Acorn production can be increased by reducing tree stand density to enhance crown development. There is less control over which trees are removed when using fire than if mechanical or chemical thinning is conducted (Dey et al., 2017). Using fire as the only management tool to reduce stem density for improved acorn production is unlikely to produce predictable results; thus, it is recommended to combine burning with thinning (Arthur et al., 2012). Masters and Waymire (2012) showed that the implementation of a burning and thinning treatments resulted in no significant difference in acorn production for post oak (*Quercus stellata*) and blackjack oak (*Quercus marilandica*) in Oklahoma.

Oaks have a moderate tolerance for living in shaded environments; thus, creating an intermediate level of light through overstory and mid-story tree removal is critical. The thinning of large unmerchantable trees is often the preferred method for achieving desired stocking conditions to increase light penetration to the understory (Dey et al., 2017). Galgamuwa et al. (2019) and Iverson et al. (2008) state that most promising results for oak regeneration were observed when combining prescribed burning with thinning.

Prescribed fire in Kansas

Prescribed burning of rangeland is a common practice in the Flint Hills region of eastern Kansas to maintain the tallgrass prairie ecosystem and improve cattle production (Liu et al., 2018). The Flint Hills contain the largest contiguous remaining area of tallgrass prairie in North America, extending from northeast Kansas down to Oklahoma, remaining practically intact as native prairie because of steep terrain and the limestone and flint outcroppings that make much of the land unsuitable for crop production (Towne & Craine, 2016).

Fire is important element in maintaining North American grasslands, and widespread use of prescribed fire in the central region of the United States, including Kansas, is used to promote livestock forage and to prevent woody species encroachment (Knapp, 2009). The use of fire in the Flint Hills dates back to pre-European settlement in the United States, when American Indians regularly burned the prairie because they observed that burned areas grew greener grasses and attracted more bison (Middendorf et al., 2009). European settlers in the late nineteenth century learned the techniques for controlled burning from American Indians to produce pasture for cattle; however, the lack of firebreaks often resulted in out of control fires. Some settlers believed that fires jeopardized the land fertility, and others wanted to replicate in Kansas the more forested environment they had previously lived in. Later, many ranchers adopted regular burning and this practice continues in the Flint Hills today.

Frequent fires help to maintain grasslands, Bragg and Hulbert (1976) observed that on unburned sites in Flint Hills, tree and shrub cover increased 34% from 1937 to 1969, and tree cover alone increased 24% from 1856 to 1969, leading to the conclusion that burning can be effective in restricting woody plants to pre-settlement conditions.

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Chapter 2 - Effects of Prescribed Burning and Thinning on Woody Vegetation in an Oak-dominated Woodland in Northeast Kansas

ABSTRACT

Periodic burning is important for the perpetuation of most oak forests because oaks are adapted to fire while competing species are more fire-sensitive. The fire suppression policies of the 20th century resulted in closed canopy environments where oaks cannot regenerate. This study was conducted on a 90-acre tract of oak-dominated woodland near Manhattan, Kansas. The study aimed to assess the effectiveness of burning and thinning to encourage oak regeneration. Our experimental design was 2 (Burn) x 2 (Thin) factorial in a repeated measures design. The resulting treatment combinations were burn and no-thin (BNT), burn and thin (BT), no-burn and thin (NBT), and no-burn and no-thin (NBNT – control). The burning and thinning operations were conducted in the Spring 2015 and Spring 2018. Vegetation inventories were done on permanent plots before burning in 2014, in the Fall 2016, and in the Fall 2018 to assess the effects of the treatments on woody vegetation composition and structure. The thinning effectively reduced the overall number of trees per acre after the second thinning operation. Burn and thin combined treatments significantly decreased the primary competitor species' basal area. While the number of oak saplings per acre was not different from the primary competitors in thinned plots, primary competitors outnumbered oak saplings in no-thin plots, and burning significantly

reduced the overall number of saplings per acre. The burn in 2018 significantly reduced the overall number of seedlings per acre. However, burn and thin treatments did not affect seedling species composition, and eastern redbud outnumbered oaks in 2018 averaged across all treatments. Two prescribed fires may not be sufficient to effectively benefit oaks.

Introduction

Periodic burning is an important element for the perpetuation and health of most oak (*Quercus* spp.) forests (Abrams, 2016). Most upland oak species have physiological adaptations to fire, such as thick bark, resprouting ability, resistance to decay after scarring, and moderately high light requirements (Abrams, 1992; Arthur et al., 2012). The fire suppression policies since the 1930s resulted in large changes in oak forests, creating closed canopy environments where oaks cannot regenerate (Abrams, 2016). A shade-tolerant midstory may become established, further exacerbating these conditions. Dense shading promotes moist, cool microclimates and the shade-tolerant, mesophytic species produce woody fuels that are not conducive to burning (Arthur, 2012). The change in species dominance caused by the suppression of fire has the potential to affect biodiversity, wildlife populations, timber production, forest hydrology, nutrient cycling, and fuel loading (Nowacki & Abrams, 2008). The reintroduction of periodic fire to restore oak forests in the eastern United States has been studied (Brose et al., 2013; Brose et al., 2014; Nowacki & Abrams, 2008). However, there are few studies from the transition area (forest-prairie ecotone) between the forested eastern United states and the Great Plains grasslands, which includes eastern Kansas.

The 2017 forest inventory in Kansas indicated a total area of 2.5 million acres of forest land, which showed a decrease of nearly 100 thousand acres from the previous inventory, in 2012 (Meneguzzo, 2018). The eastern part of the state is in the Oak Savannahs and Prairie Region (Oswalt & Olson, 2016). Dry hill tops and slopes, comprising 10% of the forest land in Kansas, are dominated by oak and eastern redcedar (*Juniperus virginiana*) forest types, which occupies 69% of these forest lands (Meneguzzo, 2018). Abrams (1986) suggested that *Quercus muehlenbergii* (chinkapin oak) is being replaced by *Cercis canadensis* (eastern redbud) on xeric sites and *Q. macrocarpa* (bur oak) is being replaced by *Celtis occidentalis* (hackberry) on mesic sites in northeast Kansas. While the use of prescribed burning is common to maintain the tallgrass prairie ecosystem in Kansas (Liu et al., 2018), it is not widely implemented as a woodland management tool.

Research in eastern forests has demonstrated promising results in reintroducing fire to encourage oak regeneration. Previous studies recommended combining chemical or mechanical thinning with fire to complete the restoration process when fire has been absent for decades because it reduces tree density, and controls the spatial arrangement and species composition of the forest (Brose et al. 2014). The objective of this study is to assess the woody species composition and structure of a woodland in northeast Kansas in response to recent prescribed fires and thinning operations.

Methods

Study Site and Experimental Design

The study was conducted at the Howe Natural Resources Education Center, a 145-acre woodland owned by the Department of Horticulture and Natural Resources, Kansas State University. The area is located north of Manhattan, Kansas, on the western edge of Tuttle Creek Reservoir. Vegetation composition is a mix of upland oak and eastern redcedar forest types, and only the oak-dominated portion was considered for this study. The site index, assessed by Galgamuwa et al. (2019) by estimating the age and measuring the height of codominant and dominant chinkapin oak trees in the area, is 40 (dominant and codominant individuals are 40 feet tall at age 50), which indicates a low-quality site.

The study area was divided into 12 compartments. Compartment area varied from 6 to 10 acres, with their boundaries delimited by natural drainages. The treatment combinations consisted of two levels of burn (burn and no-burn) and two levels of thin (thin and no-thin). The compartments were grouped into 2-compartment units (whole-plot), and three units had the burning treatment randomly assigned to them. The 2-compartment units were split into two 1-compartment units (split-plot) to randomly assign the thinning treatment. The resulting treatment combinations were burn and no-thin (BNT), burn and thin (BT), no-burn and thin (NBT), and no-burn and no-thin (NBNT) or control (Figure 2-1). One permanent circular plot per acre was installed, totaling 92 plots (Figure 2-2). These plots were used to collect inventory pre-treatment in 2014, post-treatment in 2016 and after the second treatment application in 2018.

Treatments

The inventory conducted in 2014 indicated that one compartment was overstocked, with stocking higher than 100%, and the remaining compartments were fully stocked, presenting stocking between 60% and 100% (Galgamuwa et al., 2019). In January 2015, the thinning operation was conducted to reduce the stocking. The prescription was to remove 25 trees per acre, mainly eastern redcedar (*Juniperus virginiana*), American elm (*Ulmus americana*) and hackberry (*Celtis occidentalis*) and 50 saplings per acre of American elm, eastern redbud (*Cercis canadensis*), eastern redcedar and hackberry (Galgamuwa et al., 2019). The second thinning was conducted in February 2018 and the thinning prescription varied according to the compartment stocking (Table 2-1). The size class trees was composed of trees with a diameter at breast height (dbh) larger than 5 in. (12.7 cm), and trees from 1 in. (2.45 cm) to 4.9 in. (12.45 cm) were categorized as saplings. The trees were single girdled and the saplings were completely cut and treated with a chemical mix of 25% Garlon-4 mixed with diesel fuel.

The prescribed fires were conducted by Kansas Forest Service. The first burn was a dormant season fire conducted in April 2015. Air temperature at ignition was 75˚F in 2015, with a relative humidity of 33% and a 20 ft. wind speed of 4-6 mph (Galgamuwa et al., 2019). The second fire was originally planned to be conducted after 2 growing seasons; however, due to frequent wildfires in 2017, Kansas Forest Service did not have personnel available. A test burn was conducted in May 2017, but the fire was unable to carry across the compartments. The second burn was carried out in early May 2018 due to weather restrictions and personnel constraints during the dormant season period, and the woody species were starting to leaf out. Air temperature was 75 ˚F, with relative humidity of 50% and wind speed of 7 mph. Before the second burning, aluminum tags painted with temperature sensitive paints were deployed, east and west of the plot center (two tags per plot), immediately before the burn in 2018. Each tag was folded in aluminum foil and positioned 25 cm above the ground with a pin, based on the methodology of Iverson et al. (2004). The temperatures to be recorded were 175 ˚F (79 ˚C), 300 ˚F (149 ˚C), 425 ˚F (218 ˚C), 600 ˚F (316 ˚C), 750 ˚F (399 ˚C), and 900 ˚F (482 ˚C) (Figure 2-3). A total of 16 out of 48 temperature tags on B plots did not record temperatures higher than 175 ˚F, the remaining tags recorded an average of 231.6 ˚F (110.9 ˚C), and 4 tags melted or burned.

For the BT plots, 7 out of 44 temperature tags did not reach at least 175 ˚F, while the remaining tags recorded an average of 280.9 ˚F (138.3 ˚C), and 3 tags melted or burned.

Data Collection

Data collection was conducted on all 92 permanent plots. All the trees (>5.0" dbh) located within the circular plots (1/10 acre area) were measured and identified. Two micro-plots were installed 18.5 ft from the plot center, due east (90°) and due west (270°) from the plot center. The saplings (1.0 – 4.9 in. dbh) that were found within the 11.8 ft. (3.6 m) radius micro-plot were measured to make sure they were <5 in. DBH and identified, and the seedlings (<1.0 in. dbh) present in the 6.8 ft (2.1 m) radius micro-plot (Figure 2-4) were recorded. According to Forest Inventory and Analysis (FIA) protocol, hardwood seedlings must be at least 12 in. tall and conifers must be at least 6 in tall to be considered. Since the inventory in 2018 was conducted only one growing season post-fire, seedlings smaller than 12 in. were also counted, but they were not used for the analysis.

Data Processing and Statistical Analysis

Count datasets for trees, saplings and seedlings were converted to trees per acre (TPA), saplings per acre (SapPA) and seedlings per acre (SeedPA) values by species. The dbh data for trees were used to calculate basal area per acre (BA) by species. For the final analysis, the species are categorized into interest groups: oaks (chinkapin oak [*Quercus muehlenbergii*], bur oak [*Quercus macrocarpa*], black oak [*Quercus velutina*]), other nut bearing species (black walnut [*Juglans nigra*], bitternut hickory [*Carya cordiformis*]), primary competitors (American elm, eastern redbud, eastern redcedar, hackberry), and others (green ash [*Fraxinus pennsylvanica*], honeylocust [*Gleditsia triacanthos*], Kentucky coffeetree [*Gymnocladus dioicus*], osage-orange [*Maclura pomifera*], red mulberry [Morus rubra]). Eastern redbud was considered a separate class in the seedPA analysis due to the large number of seedlings of this species.

Data analysis was conducted using the GLIMMIX procedure of SAS (version 9.4, SAS Inst. Inc.). Vegetation structure and composition was analyzed for trees (> 5.0 in. dbh), saplings (1-4.9 in. dbh) and seedlings (< 1.0 in. dbh) separately. The response variables for the trees dataset were TPA and basal area. The response variables of SapPA and SeedPA were used for saplings and seedlings datasets, respectively. Burn, thin, and group factors were treated as fixed effects with time being the repeated measure. The lognormal distribution with identity link function provided the best description of the residuals for all the analysis.

In all the analyses, the residual plots were investigated to check model assumptions. The Kenward Rogers denominator degrees of freedom method and Bonferroni adjustment for multiple comparisons were used. The LSMEANS (least squares means) option of SAS was used for multiple comparisons. Type III test of fixed effects was employed, and means were considered statistically significantly different at a *P*-value of < 0.05.

Results

Trees

The statistical analysis for trees per acre (TPA) showed significance for a two-way interaction between burn and thin treatments (P < 0.05) (Figure 2-5). No-burn and thin

(NBT) TPA was significantly smaller than burn and no-thin (BNT - 54 TPA), but not different from no-burn and no-thin (NBNT), and burn and thin (BT). BT also presented a significant decrease of 66 and 39 TPA when compared to BNT and NBNT, respectively. The total TPA was similar between BNT and NBNT. TPA was also significant for the two-way interaction between thin and time ($P < 0.01$). The TPA after thinning treatment in 2018, averaged across burn and no-burn, was smaller than the thinning in 2014 and 2016 (Figure 2-6), and than no-thin in 2018 (Figure 2-7). The total TPA decreased by 35 from 2016 to 2018 with the thinning treatment, and it had 72 TPA less than the no-thin compartments in the same year. The two-way thin and group interaction was also highly significant ($P < 0.001$). Oaks were the most abundant species both in thin (86 TPA) and no-thin (73 TPA) treatments. The most relevant difference was that, while in no-thin compartments the oaks TPA was statistically the same as the primary competitors TPA, the thinning treatment substantially reduced the primary competitors (72 TPA less than oaks) (Figure 2-8). A two-way interaction between burn and group ($P < 0.0001$) was observed for TPA (Figure 2-9). Oaks were the most abundant species, both for burn and no-burn (approximately 80 and 78 TPA, respectively). The other nut bearing species had higher numbers in the unburned compartments (27 TPA against 14 in burned compartments). The species classified as “others” were the least abundant, and in no-burn compartments they were even less frequent than in the burn ones (less 4 TPA), and there were not differences between the treatments for the primary competitors.

Tree basal area presented significance for three-way burn, thin and group interaction ($P < 0.05$). Oaks had the highest BA in all treatment combinations. BT compartments had a significantly lower BA of the primary competitors when compared to oaks (87 ft^2/acre) (Figure 2-10), and BA of the primary competitors in BNT (Figure 2-11). Two-way interaction between thin and time ($P < 0.05$) was observed. While there was no evidence that the thinning plots BA in 2014 and 2016 was lower than the no-thin plots, in 2018 the difference was significant. The compartments where the thinning was conducted presented 72 ft^2/acre less than the no-thinned compartments in the same year (Figure 2-12).

Saplings

Two-way interaction between thin and group ($P < 0.05$) was observed. When considering no-thin plots, the number of oak SapPA was smaller than the primary competitors, with a difference of 83 SapPA (Figure 2-13). The number of oak SapPA in thinned compartments was not statistically different from SapPA of the primary competitors both in burn and no-burn. SapPA were significantly reduced ($P < 0.01$) by the burn treatments, resulting in approximately 43 less SapPA in the burned compartments, averaged across thin and no-thin (Figure 2-14). Time ($P < 0.01$) effect was also significant, and the number of SapPA reduced significantly from 2014 to 2018 (57 SapPA), while the reduction was not significant from 2014 to 2016, and from 2016 to 2018 (Figure 2-15).

Seedlings

Two-way interaction between burn and time was significant ($P < 0.001$) and showed that the total number of seedlings reduced 330 SeedPA from 2016 to 2018 in the burned compartments, averaged between thin and no-thin, while there was no evidence of differences after the first burning and in the unburned compartments (Figure 2-16). The two-way interaction between time and group was also significant ($P < 0.001$). While there was no evidence of differences in the number of eastern redbud SeedPA and oaks in 2014 and 2016, eastern redbud outnumbered oaks by 241 SeedPA in 2018 (Figure 2-17). SeedPA of the other primary competitors decreased 325 when comparing 2016 and 2018 inventory (Figure 2-18). SeedPA was significantly ($P < 0.05$) reduced by thinning, resulting in 349 SeedPA less than no-thin.

Seedlings smaller than 12 inches

Eastern redbud outnumbered oaks in BT, BNT and NBT plots, but not in NBNT plots (Figure 2-19). However, it is not possible to guarantee that these oak seedlings that were found in the undisturbed plots are going to persist and reach a competitive position living in such a shaded environment. Burn, and burn and thin combined seems to have negatively influenced the other primary competitors, considering that they presented a more comparable number to oaks in NBT and NBNT than in BT and BNT (Table 2-2). The ratio of oaks/primary competitors was approximately 1:1 in NBNT and NBT, 1.5:1 in BNT and 3:1 in BT.

Discussion

Considering that oaks have low to intermediate tolerance to shade, creating canopy openings is important to stimulate oak seedling development. Thinning is more effective than fire for selective removal of trees, managing understory light and meeting desired stocking conditions (Arthur et al., 2012; Dey et al., 2017). In these study results, while BNT overstory was not statistically different from NBNT, the burn and thin treatment combination (BT) did result in a significantly lower number of TPA. Thinning treatment was successful in decreasing the density of the primary competitor species, and the total TPA in 2018. When considering the saplings, thinning affected the species composition by selectively removing oak competitors, while burning affected the total SapPA, which reinforces the efficacy of thinning to reduce undesired species.

The SeedPA analysis showed that burn had an effect over time on total SeedPA, but not on species composition. The species composition change over time was not different among the treatment combinations. These results are similar to Alexander et al. (2008), where oak survival and growth remained similar to or lower than on unburned controls. Franklin et al. (2003) observed that structural changes in the forest due to disturbance treatments are more evident than compositional changes.

It is important to consider that the 2018 inventory was done just four to five months after the fire, so the results may change after one more growing season, mainly for the SeedPA data, since many seedlings might not have reached 12 inches after only one growing season. The small seedlings (<12 in.) were not included in the analysis because 2018 was the only year this data was collected. Small seedlings living in a shaded environment can reach about a foot and remain in the understory for many years until they eventually die (Schweitzer et al., 2016).

Moreover, even the thinning treatment may not yet have increased understory light to provide an adequate environment for oak regeneration, since thinning was significant only for 2018 and the trees were girdled, which does not kill the tree immediately. Furthermore, the oak seedlings may have only a small root system to support their resprouting ability as a result of living in a shaded environment (Brose et al., 2014).

If a shade-tolerant understory remains after the treatments, there is no increased competitiveness for oaks (Moser et al, 1996). Oaks did not outcompete the other species after the fire possibly because the fire was conducted in early-May so the seedlings may have already begun expanding their leaves, utilizing root carbohydrate reserves (Brose et al., 2014).

The effect of conducting several burns to influence today's forest dynamics, after decades without fire, is unlikely to immediately achieve abundant oak regeneration, even though fire still affects vegetation (Arthur et al., 2012; Franklin, 2003). Furthermore, low intensity fires often have little effect on species composition (Kuddes-Fischer & Arthur, 2002). Lorimer (1992) reported that nearly all of the studies reporting increases in oak seedling establishment involved several burns.

After the first burning of this study, Galgamuwa et al. (2019) suggested that the fully stocked conditions and eastern redbud recovery persisting post-fire could be detrimental to the oak regeneration, and that controlling eastern redbud is a major challenge. These conditions did not change after the second burning, as eastern redbud regeneration rates remained the same over time. Eastern redbud regeneration was superior to oak regeneration in 2018, regardless of the treatment combination. Sullivan (1994), in a review about eastern redbud species characteristics, states that it may behave as a fire tolerant species, sprouting vigorously after top-kill by one fire; however, the same author indicates it is not usually a member of communities which experience frequent fire.

The results obtained after the second burning and thinning operations showed that while thinning was effective in selectively removing saplings and trees of undesired species, two burnings treatment were not effective in increasing oak competitiveness.

Another inventory needs to be conducted to assess the seedling composition after one more growing season, and if there is no evident compositional change, a third burn may be conducted.

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Table 2-1: Thinning Prescription in 2018

Compartment	TPA	SapPA	Additional Recommendations
1	25	20	first the non-oak were removed, then oak if needed
3	25	50	primarily cedar, hackberry and hickory were removed
5	25	50	primarily cedar, hackberry and hickory were removed
7	30	20	first the non-oak were removed, then oak if needed
10	5	20	cedar was the priority, then other non-oak species, especially elm saplings
11	40	0	first the non-oak were removed, then oak if needed

Table 2-2: SeedPA of seedlings smaller than 12 inches

SeedPA	NBNT	NBT	BNT	BT
Oaks	1147	478	680	257
Primary Competitors	1077	413	420	87
Redbud	583	748	920	617
Nut bearing species	290	220	317	370
Others	107	35	77	13

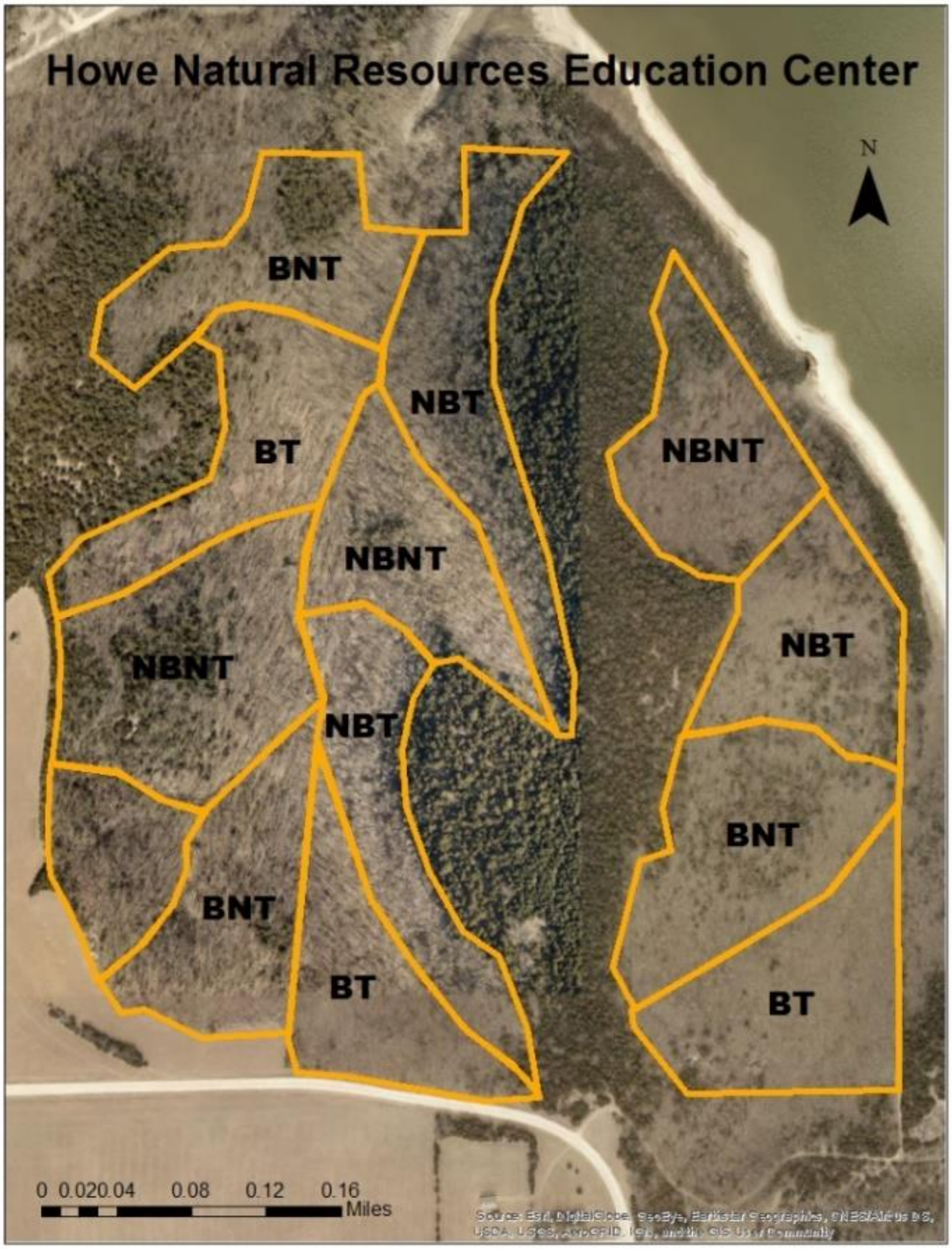

Figure 2-1: Study area and treatment design. NBNT = no-burn and no-thin (control), NBT = no-burn and thin, BNT = burn and no-thin, BT = burn and thin.

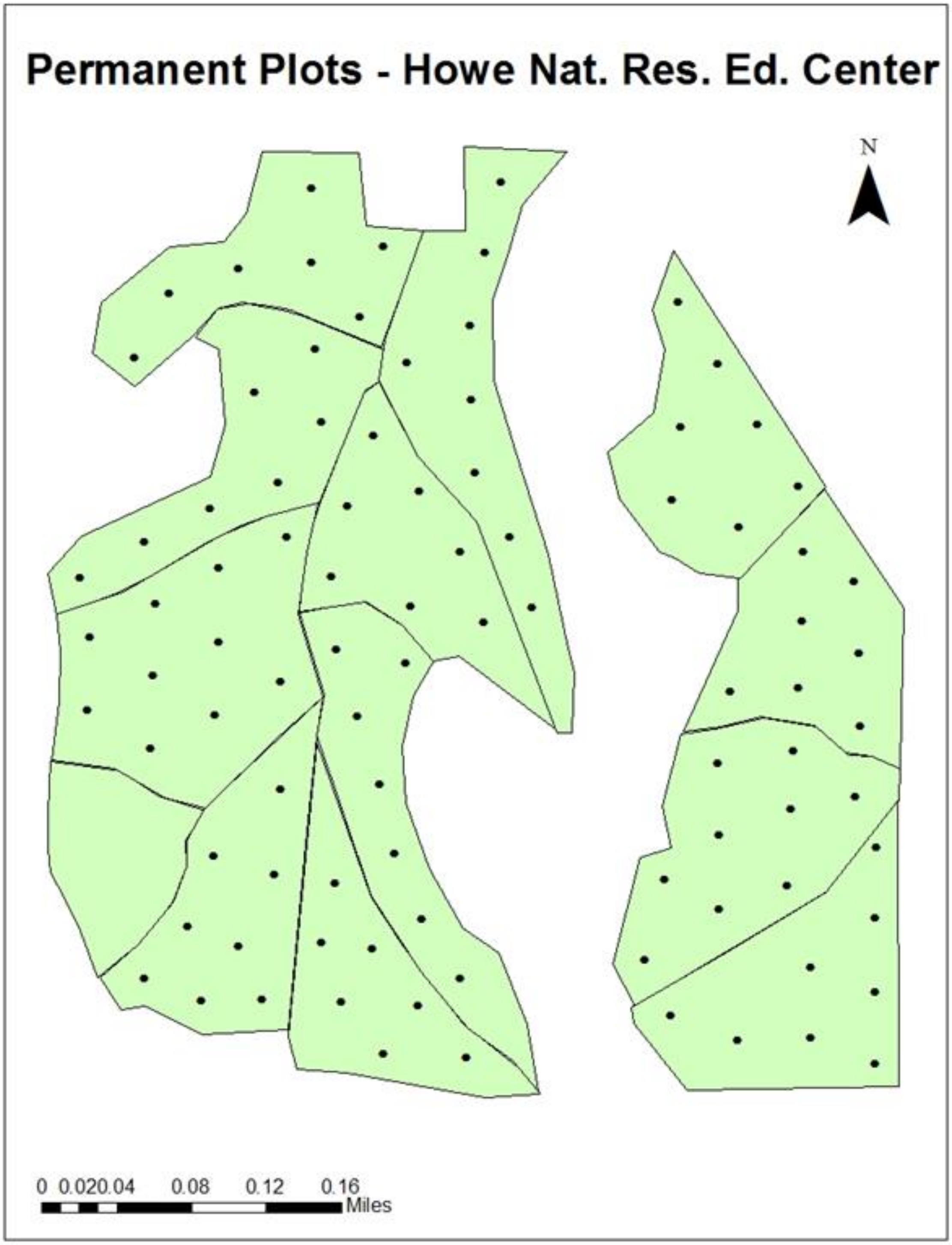

Figure 2-2: Data collection permanent plots

Figure 2-3: Temperatures recorded by the tags

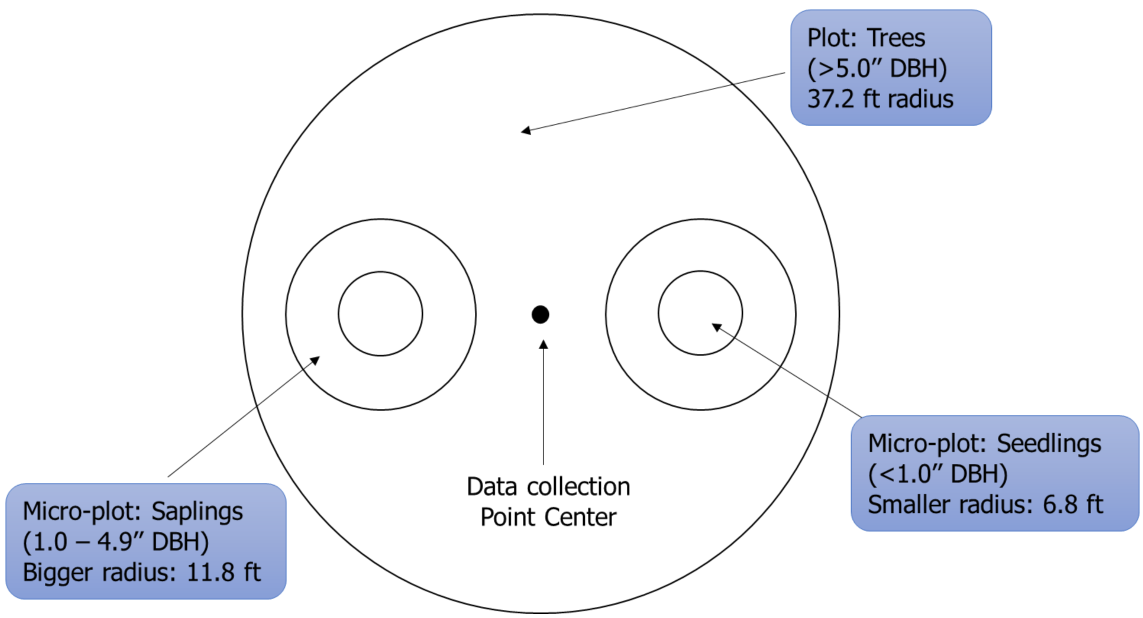

Figure 2-4: Inventory Plots

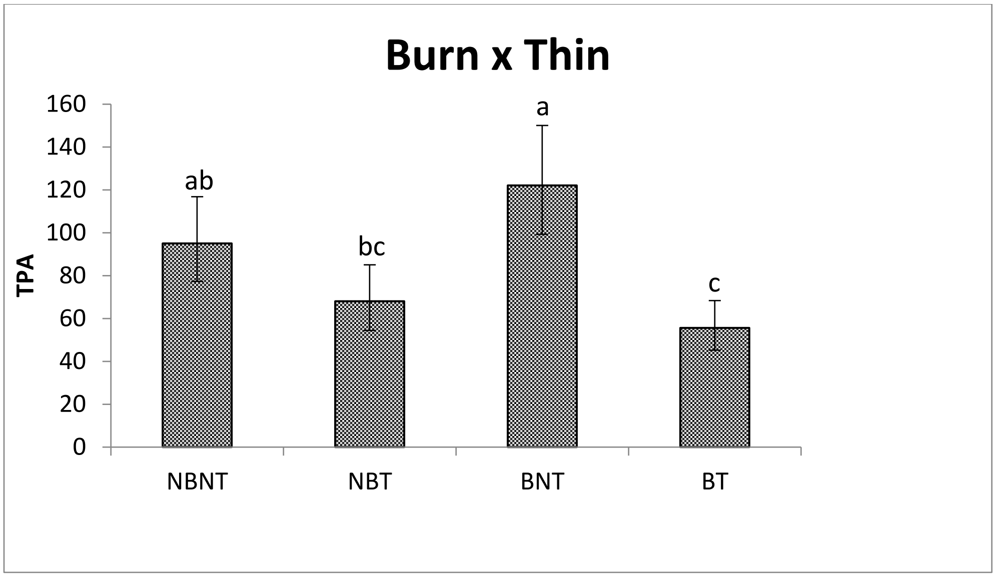

Figure 2-5: TPA burn and thin two-way interaction. Means with the same letter are not significantly different. NBNT = no-burn and no-thin, NBT = no-burn and thin, BNT = burn and no-thin, BT = burn and thin.

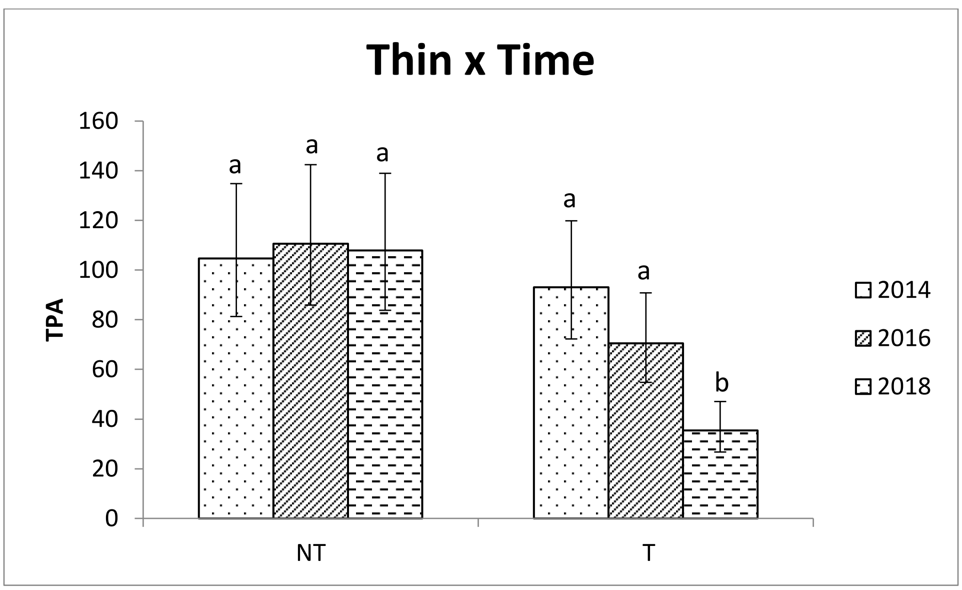

Figure 2-6: TPA thin and time two-way interaction. Comparisons are within each level of thin. Means with the same letter are not significantly different. NT = no-thin, T = thin.

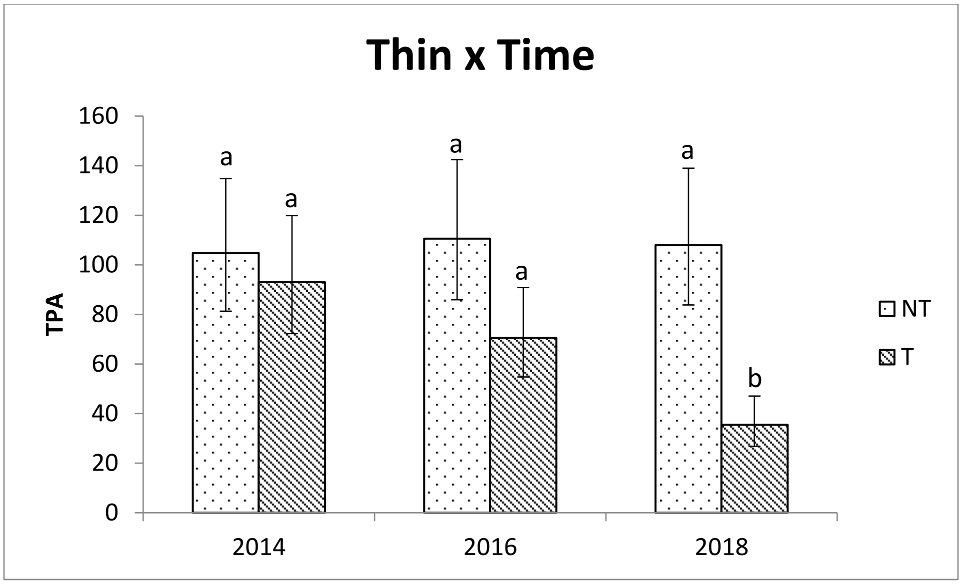

Figure 2-7: TPA thin and time two-way interaction. Comparisons are within each year. Means with the same letter are not significantly different. NT = no-thin, T = thin.

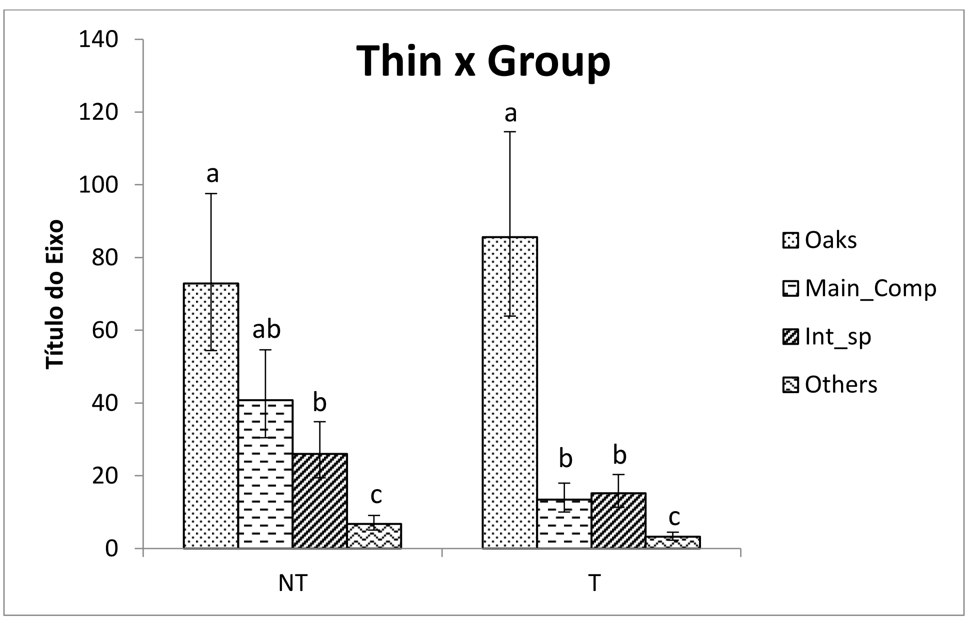

Figure 2-8: TPA thin and group two-way interaction. Comparisons are within each level of thin. Means with the same letter are not significantly different. NT = no-thin, T = thin. Oaks = oaks, Main_Comp = primary competitors, Int_sp = other nut bearing species, Others = other species.

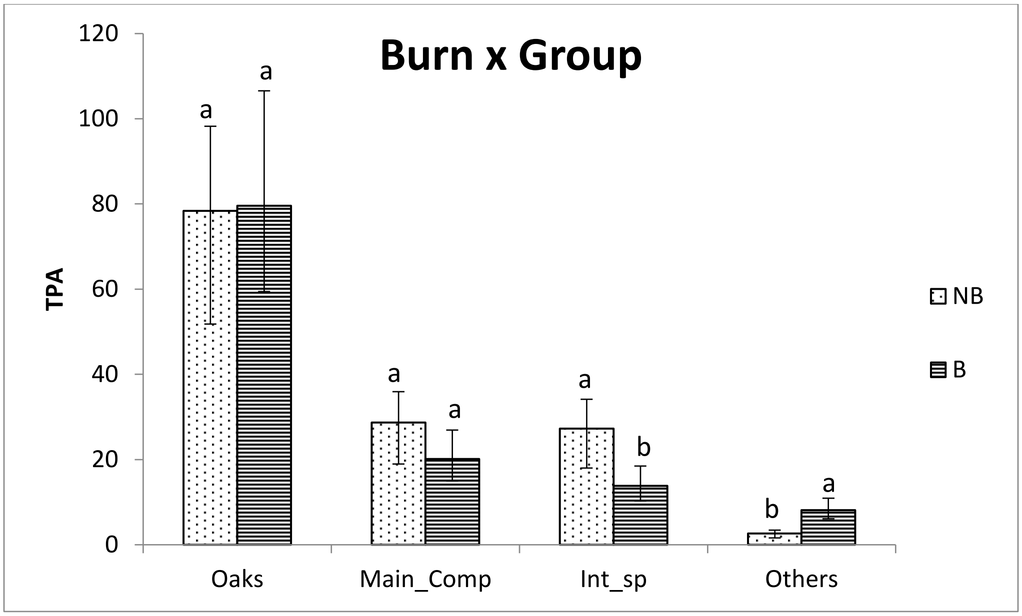

Figure 2-9: TPA burn and group two-way interaction. Comparisons are within each group. Means with the same letter are not significantly different. Oaks = oaks, Main_Comp = primary competitors, Int_sp = other nut bearing species, Others = other species. NB = no-burn, B = burn.

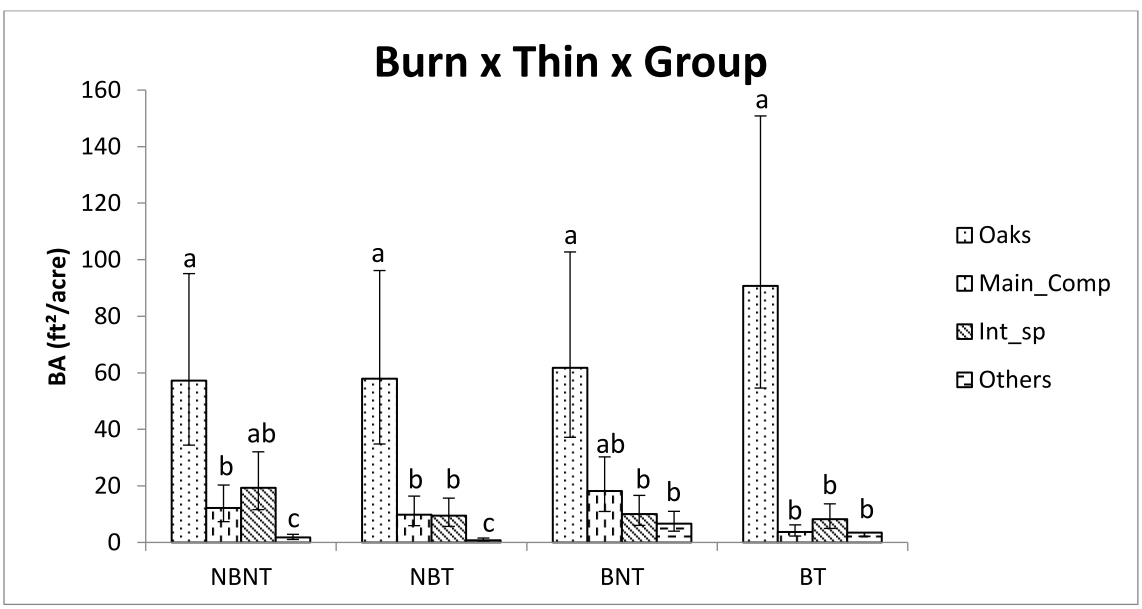

Figure 2-10: BA burn, thin and group three-way interaction. Comparisons are within each treatment combination. Means with the same letter are not significantly

different. NBNT = no-burn and no-thin, NBT = no-burn and thin, BNT = burn and no-thin, BT = burn and thin. Oaks = oaks, Main_Comp = primary competitors, Int_sp = other nut bearing species, Others = other species.

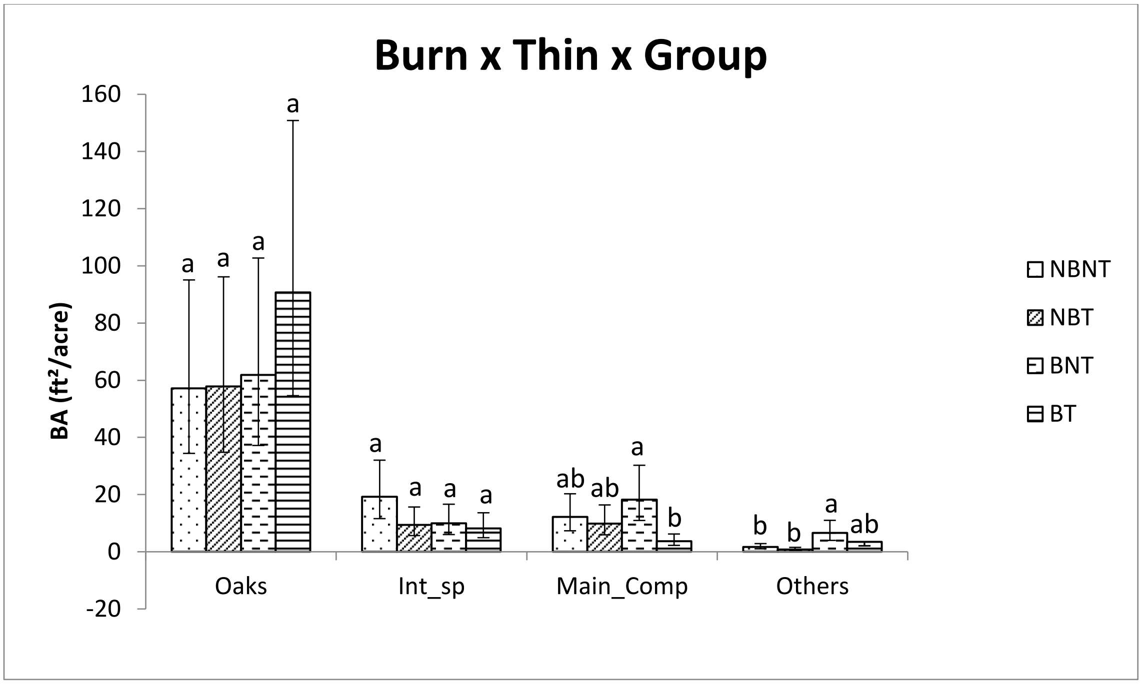

Figure 2-11: BA burn, thin and group three-way interaction. Comparisons are within each group. Means with the same letter are not significantly different. Oaks = oaks, Main_Comp = primary competitors, Int_sp = other nut bearing species, Others = other species. NBNT = no-burn and no-thin, NBT = no-burn and thin, BNT = burn and no-thin, BT = burn and thin.

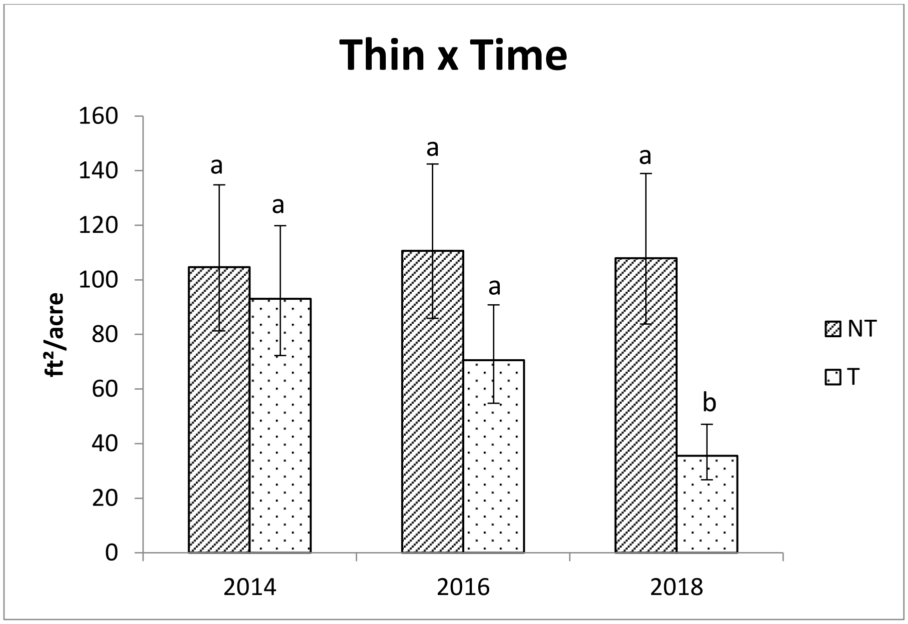

Figure 2-12: BA thin and time two-way interaction. Comparisons are within each year. Means with the same letter are not significantly different. NT = no-thin, T = thin.

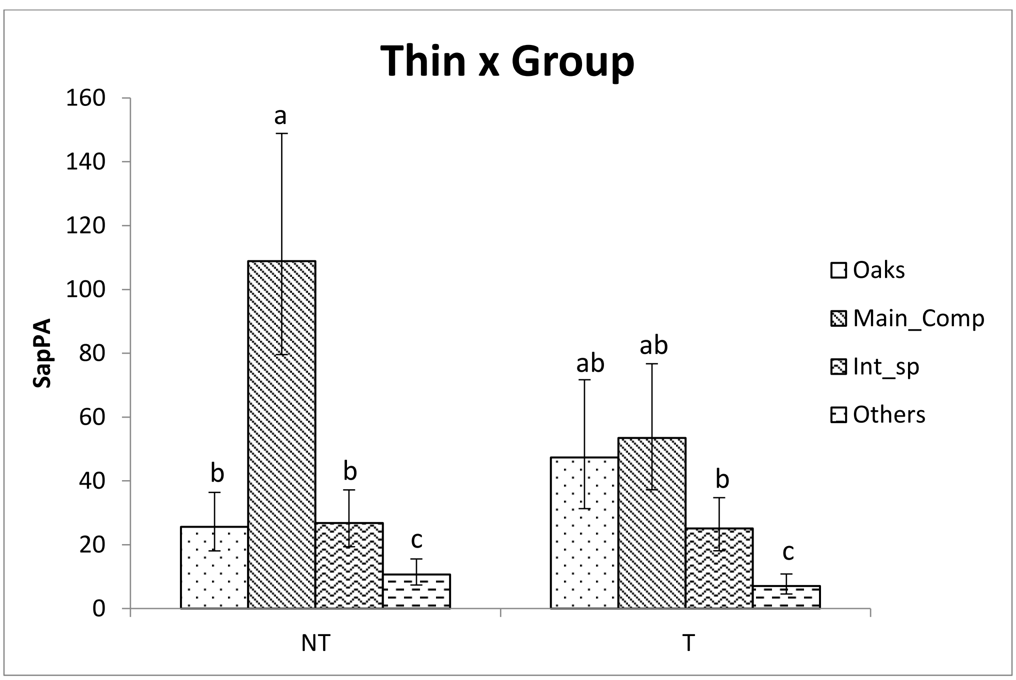

Figure 2-13: SapPA thin and group two-way interaction. Comparisons are within each level of thin. Means with the same letter are not significantly different. NT = no-thin, T = thin. Oaks = oaks, Main_Comp = primary competitors, Int_sp = other nut

bearing species, Others = other species. Oaks = oaks, Main_Comp = primary competitors, Int_sp = other nut bearing species, Others = other species.

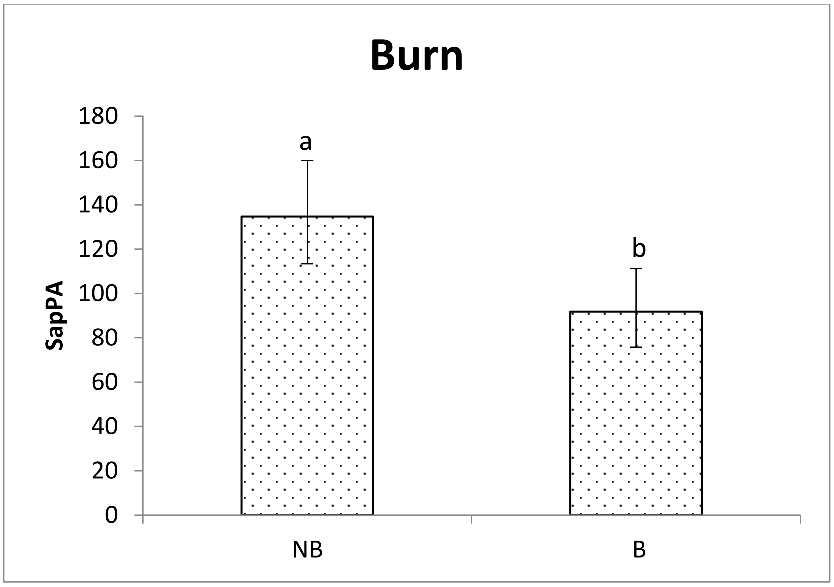

Figure 2-14: SapPA burn effect. Means with the same letter are not significantly different. NB = no-burn, B = burn.

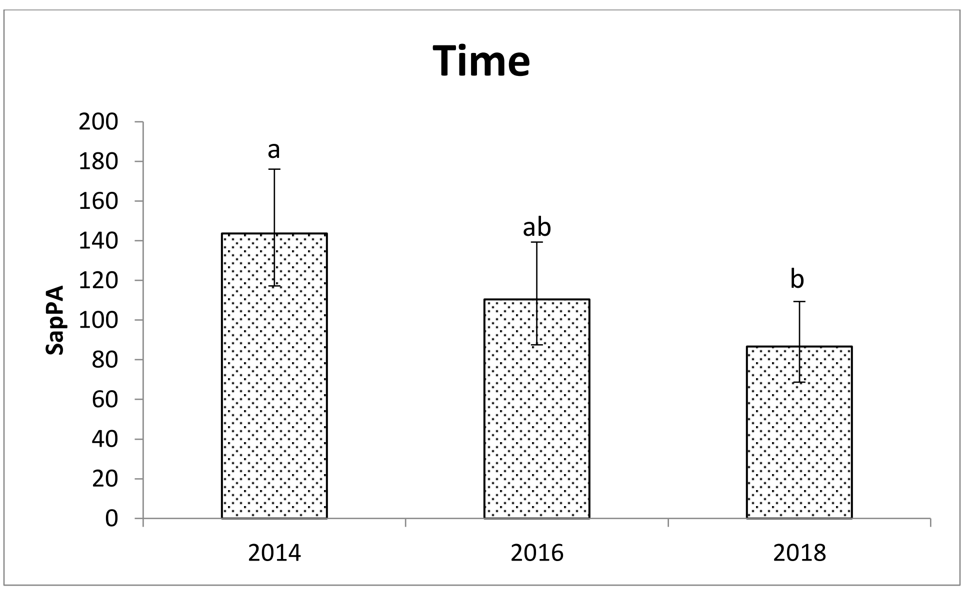

Figure 2-15: SapPA time effect. Means with the same letter are not significantly different.

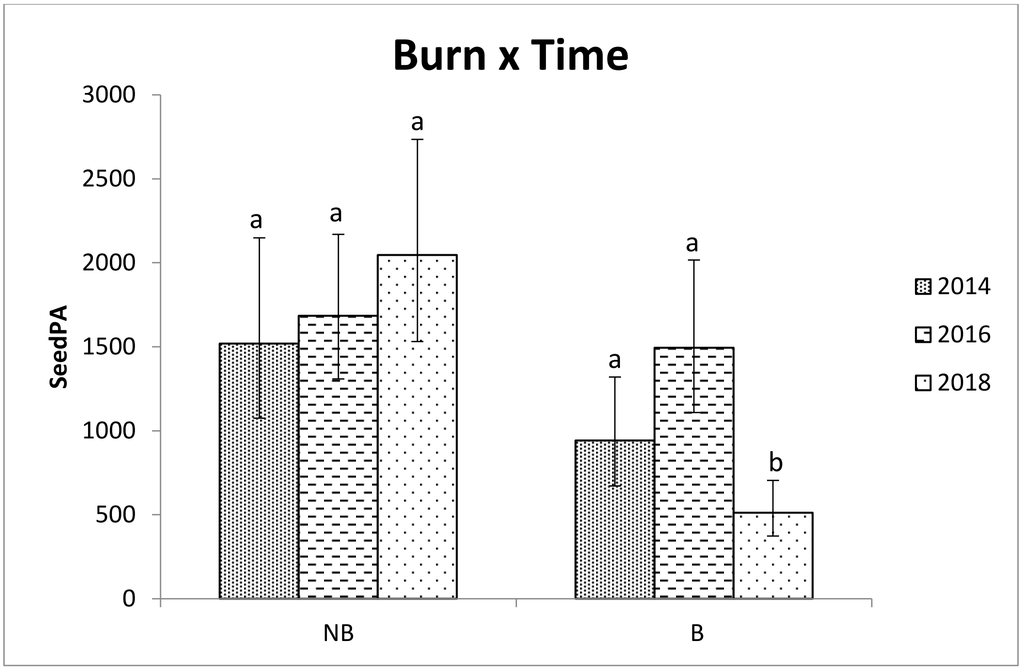

Figure 2-16: SeedPA burn and time two-way interaction. Comparisons are within each level of burn. Means with the same letter are not significantly different. NB = no-burn, B = burn.

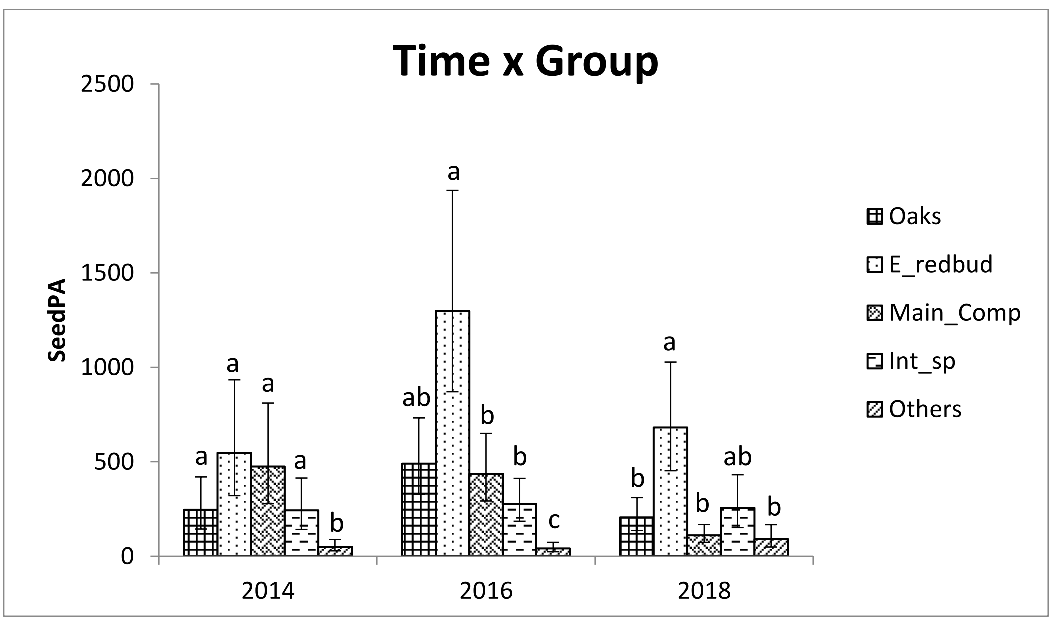

Figure 2-17: SeedPA time and group two-way interaction. Comparisons are within each year Means with the same letter are not significantly different. Oaks = oaks, Main_Comp = primary competitors, Int_sp = other nut bearing species, Others =

other species. Oaks = oaks, Main_Comp = primary competitors, Int_sp = other nut bearing species, Others = other species.

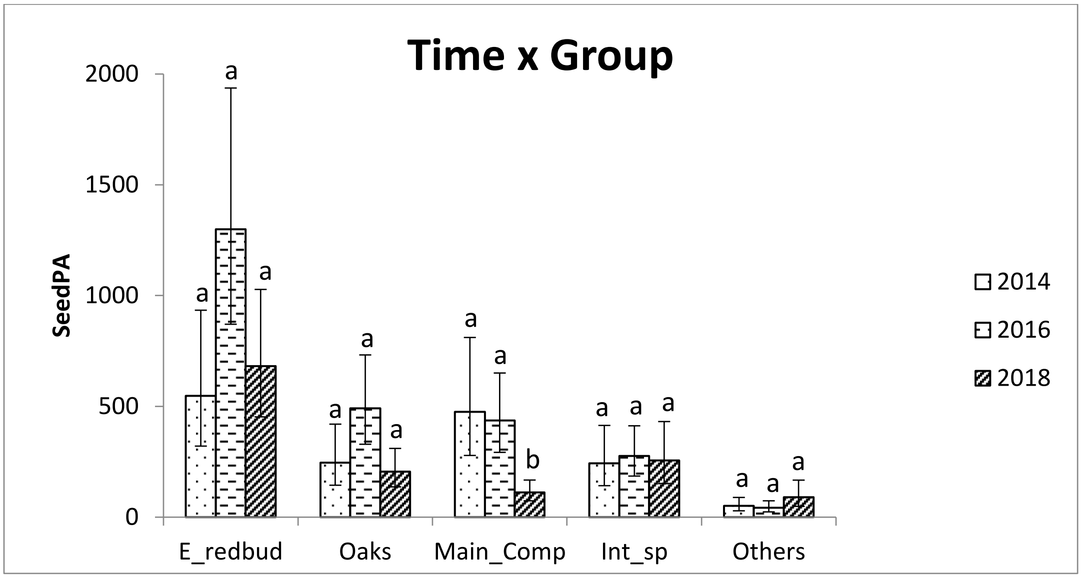

Figure 2-18: SeedPA time and group two-way interaction. Comparisons are within each group. Means with the same letter are not significantly different. Oaks = oaks, Main_Comp = primary competitors, Int_sp = other nut bearing species, Others = other species.

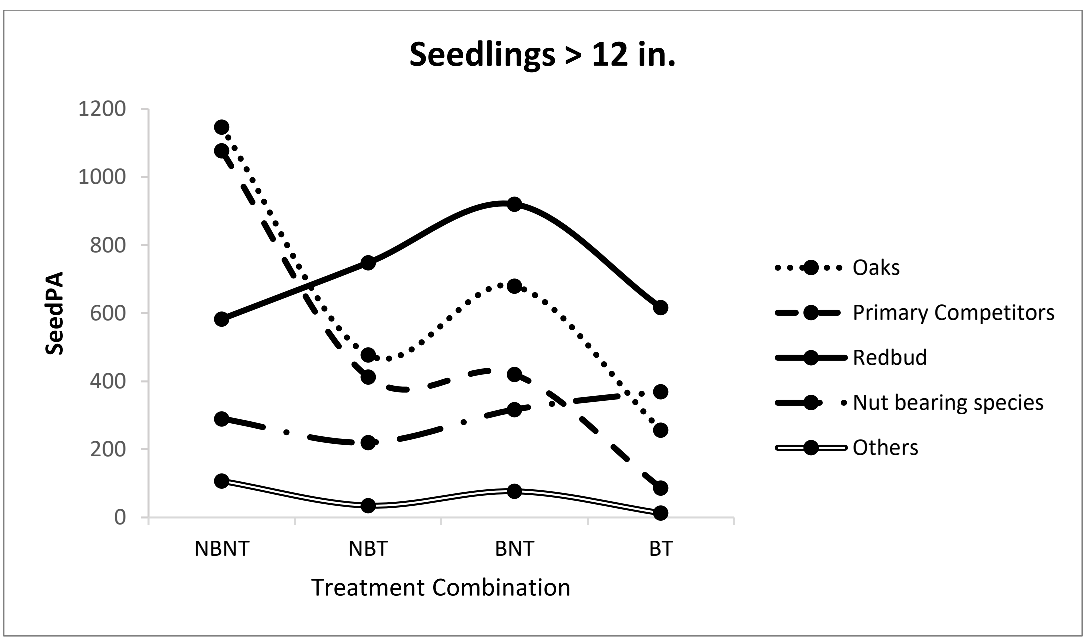

Figure 2-19: SeedPA smaller than 12 inches.

Chapter 3 - Effects of Burning and Thinning on Fuel Loading and Recovery in an Oak-dominated Woodland in Northeast Kansas.

ABSTRACT

Mature oak woodlands are being replaced by mesophytic, shade-tolerant forests across the eastern United States. The shift from oak to mesophytic species, caused by the fire suppression policies, resulted in less flammable forest floors. This study was conducted on a 90-acre tract of oak-dominated woodland near Manhattan, Kansas. The study aimed to assess the fuel loading and consumption after prescribed fires and thinning operations were conducted. The experimental design was 2 (Burn) x 2 (Thin) factorial in a repeated measures design. The resulting treatment combinations were burn and no-thin (BNT), burn and thin (BT), no-burn and thin (NBT), and no-burn and no-thin (NBNT – control). The burning and thinning operations were conducted in the Spring 2015 and Spring 2018. Fuel loading was measured pre- and post-burning, in 2015 and 2018, using both nondestructive (sampling plane or transect method) and destructive methods (quadrat method), to evaluate fuel consumption and recovery. Overall, both methods showed the same trends for the fuels; however, the quadrat method was more conservative. There was a significant recovery of litter fuel load from 2015 to 2018 and a significant decrease from pre- to post-burning in 2018 of the litter and duff layer. The quadrat method presented interaction

between time and thin for litter. Total fuel load consumption was significant only in 2018 and 1000-hr sound fuel was the only fuel affected by thinning.

Introduction

Mature oak (*Quercus spp.*) forest regeneration has been a challenge for land managers throughout eastern North America, and the stands are being replaced by mesophytic, shade-tolerant hardwoods (Brose et al., 2013). In Kansas, hackberry (*Celtis occidentalis*) is replacing bur oak (*Q. macrocarpa*) on mesic sites, and eastern redbud (*Cercis canadensis*) is substituting chinkapin oak (*Q. muehlenbergii*) on xeric sites (Abrams, 1986). Prescribed fire has been used as a management tool to restore oak woodlands in the eastern United States because oaks have physical and physiological adaptations that allow them to survive at higher rates than their competitors under a periodic fire regime (Brose et al., 2013; Nowacki & Abrams, 2008). While prescribed fire is used to maintain the tallgrass prairie ecosystem in Kansas (Liu et al., 2018), it is not widely implemented as a management tool for woodland restoration.

The compositional shift from oak to mesophytic species caused by the fire suppression policies implemented since the 1930s has resulted in less flammable forest floors through dampness and moisture-accelerated decomposition of fuels (Abrams, 2016; Nowacki & Abrams, 2008). Thus, it is important to reintroduce periodic fires to encourage oak regeneration and restore the composition and quality of the litter to improve the conditions for efficient fires and fire-adapted species.

A contiguous fuel bed and an adequate fuel load are essential to conduct the fire, and to maintain it long enough to kill competing species and provide sufficient time for oak seedling establishment (Frelish et al., 2015). The fuel bed is composed of duff, leaf litter, fine twigs (1- hour and 10-hour fuels), medium-diameter branches (100- hour fuels), and large logs (1000-hour fuels) that are typically not consumed in fires (Frelish et al., 2015). Inventory of fuel loading can help to practice fuel management, plan for prescribed fire, and estimate utilization potential (Brown, 1974). The effects of prescribed burning and thinning treatments on fuels are not completely understood, and this understanding is important since these management tools are often used for restoration of habitat and biodiversity (Kolaks et al., 2004). The objective of this study is to assess the effects of two burns and two thinning operations on fuel consumption and recovery in an oak-dominated woodland in the forest-prairie ecotone of Kansas.

Methods

Study site and experimental design

The site where the study was conducted was the Howe Natural Resources Education Center, which includes a 145-acre woodland composed of upland oak and eastern redcedar forest types. The area is owned by the Department of Horticulture and Natural Resources, Kansas State University, and it is located north of Manhattan, KS, on the western edge of Tuttle Creek Reservoir. Only the oak-dominated portion was included for this research.

The study area was divided into 3 blocks according to topographic characteristics, and each block was composed of 4 compartments, totaling 12 compartments, each one containing between 6 and 10 acres, with their boundaries determined by natural drainages. Each of the compartments within a block had a different treatment combination applied to it. The combinations consisted of two levels of burn (burn and no-burn) and two levels of thin (thin and no-thin). Within a block, compartments were grouped into 2-compartment units (whole-plot), and one of the 2-compartment units had the burning treatment randomly assigned to it. The 2-compartment units were split into two 1-compartment units (split-plot) and thinning treatment was randomly assigned to one of them. The resulting treatments combinations were burn and no-thin (BNT), burn and thin (BT), no-burn and thin (NBT), and no-burn and no-thin (NBNT) or control (figure 3-1). Ninety-two (92) permanent circular plots were installed, with the frequency of at least one plot per acre.

Treatments

In January 2015, the first thinning operation was conducted, aiming to remove 25 trees per acre, mainly eastern redcedar, American elm and hackberry, and 50 saplings per acre of American elm, eastern redbud, eastern redcedar and hackberry (Galgamuwa et al., 2019). The second thinning was conducted in February 2018 and the prescription varied according to the compartment stocking (Table 3-1). A woody plant was considered a tree if its diameter at breast height (dbh) was larger than 5 in. (12.7 cm), and young trees from 1 in. (2.45 cm) to 4.9 in. (12.45 cm) dbh were considered saplings. The trees were single girdled and the saplings were completely cut and treated with a chemical mix of 25% Garlon-4 mixed with diesel fuel.

Both burns were conducted by the Kansas Forest Service. The first burn was conducted in April 2015, air temperature at ignition was 75˚F, with a relative humidity of 33% and a 20 ft. wind speed of 4-6 mph, and it was a dormant season burn (Galgamuwa et al., 2019). The second fire was originally planned to be conducted after 2 growing seasons; however, due to frequent wildfires in 2017, Kansas Forest Service did not have personnel available. A test burn was conducted in May 2017, but the fire was unable to carry across the compartments. The second burning was carried out in May 2018 due to weather conditions and personnel constraints during the dormant season. Since the plants had started to leaf out, it could be considered an early growing season fire. Air temperature was 75 ˚F, with relative humidity of 50% and wind speed of 7 mph. Two aluminum tags painted with temperature sensitive paints were deployed per plot (east and west of the plot center) immediately before the burning in 2018 (Figure 3-2). They were folded in aluminum foil and deployed 25 cm above the ground, based on Iverson et al. (2004) methodology. The temperatures to be recorded were 175 ˚F (79 ˚C), 300 ˚F (149 ˚C), 425 ˚F (218 ˚C), 600 ˚F (316 ˚C), 750 ˚F (399 ˚C), and 900 ˚F (482 ˚C). A total of 16 out of 48 temperature tags deployed on BNT plots did not record temperatures higher than 175 ˚F, the remaining tags recorded an average of 231.6 ˚F (110.9 ˚C) and 4 tags melted or burned beyond recognition. For the BT plots, 7 out of 44 temperature tags did not reach at least 175 ˚F, while the remaining tags recorded an average of 280.9 ˚F (138.3 ˚C), and 3 tags melted or burned.

Data Collection

38 of the 92 permanent plots (at least 3 per compartment) were selected to collect fuel loading data (Figure 3-3) immediately before and after the fire, both in 2015 and 2018. The "fuel load (FL)" sampling protocol of fire effects and monitoring system (FIREMON) (Lutes et al., 2006) was followed to sample dead and downed woody debris (DWD), and duff/litter profiles. To measure DWD, the planar intercept method (Brown, 1974) was used. Four 75-ft. (22.86 m) transects were established at each data collection plot at four aspects, starting from the plot center: 90°, 330°, 270°, and 210° (Figure 3-4). The DWD were

divided into the standard size classes of 1-hour (0.0 to 0.25 in.), 10-hour (0.25 to 1.0 in.), 100-hour (1.0 to 3.0 in.) and 1000-hour (greater than 3.0 in.) fuels. The 1-hr, 10-hr, and 100-hr fuel classes are identified as fine woody debris (FWD), and the 1000-hr fuels are classified as coarse woody debris (CWD). The classification is based on the time each size class takes to adjust to moisture conditions. All the DWD that intercepts an imaginary sampling plane extending 6 ft. vertically above the ground were measured and recorded. All the 1-hr and 10-hr fuels that crossed the sampling plane from 15 to 21 ft were counted, while the 100-hr were tallied from 15 to 30 ft, and the 1000-hr fuels had their number, diameter, decay class recorded if they crossed the sampling plane from 15 to 75 ft.

Litter/ duff profile was assessed at 45 ft. and 75 ft. along the sampling plane. Depth of the litter layer and duff layer were measured. A destructive sample was collected using a 2.7 ft^2 (0.25 m^2) quadrat. The total content of the forest floor within the quadrat down to the top of the mineral soil was collected. Non-woody vegetation samples were collected using the quadrat method. The forest floor samples were separated into duff, litter, 1-hr, 10-hr and 100-hr fuel classes. The FL and vegetation samples were oven dried to a constant weight at 65 °C and the dry weights were recorded.

The FL inventory was conducted in the B and BT compartments. The inventory was done immediately before and immediately after the burn treatment was applied, in 2015 and 2018. FL data collection was conducted at T and C compartments in 2015 and 2018 as well. The understory vegetation sampling was conducted before leaf-fall in fall 2014, fall 2016 and fall 2018.

Data processing and statistical analyses

The data collected according to the FIREMON protocol was processed using the FFI-Lite version 1.05.04.00 database management software (Lutes et al., 2009), which reports average FL in tons per acre of each fuel component for each plot. FFI-Lite uses equations described in the "Handbook for inventorying downed woody material for biomass calculation" (Brown, 1974). The fuels were classified as litter, duff, 1-hr, 10-hr, 100-hr, 1000-hr sound, 1000-hr rotten, FWD, DWD, litter and 1-hr combined, litter and DWD combined, total, litter depth and duff depth.

The data collected using the quadrat were organized into litter, duff, 1-hr, 10-hr, FWD, litter and 1hr combined, litter, duff and FWD combined, and the total. This method was unable to collect a representative sample from 100-hr and above fuel classes. The quadrat-based FL data were extrapolated to tons per acre to be comparable with the transect based method.

Statistical analysis was carried out using the GLIMMIX procedure of SAS (version 9.4, SAS Inst. Inc.). the fuel loading was analyzed in B and BT treatment combinations by comparing the pre-and post-burn data of 2015 and 2018. The fixed effect was thin, the random effect was block, and the repeated measure was time. The studentized residual plots were checked for model assumptions, and therefore either a gaussian or a lognormal distribution with an identity link function was used. To deal with unequal variances in the data, the data with similar variances were grouped for the analysis. The best covariance structure was chosen based on the model-fit parameters. Kenward Roger denominator degrees of freedom method was used as an adjustment for the unbalanced nature of the dataset. Result interpretations were conducted based on the type III tests of fixed effects, considering statistical significance at a *P*-value of < 0.05, and Bonferroni adjustment for multiple comparisons was utilized.

Results

Transect Method

The transect based method for litter comparison was significant for time effect (P < 0.01). A significant time effect suggests that the difference in case of fuel consumption can be due to the burning, independently of the thinning treatment. No statistical significance was identified after the first burning; however, the reestablishment of the litter layer from post burn 2015 to pre burn 2018 was significantly different, presenting an increase of 7.5 tons per acre (Figure 3-5). The litter reduction after the second burning was statistically significant when compared to pre burning 2018, decreasing 8.6 tons per acre. For the duff layer, time effect was significant (P < 0.01). When making pairwise comparisons, no statistical significance was found in duff loading pre-burn 2015, post-burn 2015, and pre-burning 2018; nonetheless, the duff consumption after the fire in 2018 was significant, consuming approximately 4.2 tons per acre (Figure 3-6).

When analyzing 1-hr fuels, time effect was significant (P < 0.01). After the first burning, the 1-hr fuel consumption was 0.1 tons per acre. It recovered significantly from 2015 to 2018 (0.1 tons per acre), but the reduction after the second burning was not significant (Figure 3-7). 1000-hr sound fuel analysis showed that time (P < 0.05) and thin (P < 0.05) effects were significant for the model. The estimate means were not significantly different in all four time points; nonetheless, the thinned compartments presented higher

1000-hr sound fuel loading compared with no-thin compartments, with a statistically significant difference of 1.8 tons per acre (Figure 3-8). Thus, the thinning treatment, as expected, increased the 1000-hr fuel loading. For 1000-hr rotten, time effect was significant for the model ($P < 0.05$), but no difference between the means was found when performing pairwise comparisons.

Litter and 1-hr fuel combined resulted in a highly significant time effect ($P < 0.001$). After the first burning, litter and 1-hr fuel combined were significantly reduced (decrease of 5.2 tons per acre). From 2015 to 2018, these fuels were recovered (8 tons per acre increment) and they were significantly reduced after the second burning, decreasing approximately 8.7 tons per acre (Figure 3-9). Total fuel layer presented significance in time effect ($P < 0.05$). After the burning in 2015, and from 2015 to 2018, no significant difference was found; however, after the burning in 2018 the total fuel consumption was significant (13 tons per acre) (Figure 3-10).

When considering litter layer depth, time effect was highly significant ($P < 0.0001$). The litter depth significantly decreased 1 inch after the burning in 2015, and the depth increment was significant (1.6 inches) from 2015 to 2018. After the burning in 2018, the fire significantly consumed 1.74 inches of litter layer (Figure 3-11). For duff depth, time was significant for the model, but when making pairwise comparisons, no difference was found. Considering the total depth of litter/duff layer, time effect was highly significant ($P < 0.0001$). The fire significantly consumed 1.6 inches. After 3 years, the recovery was significant (2 inches), and the consumption of 2.2 inches after the second burning was significant (Figure 3-12).

The changes in fuel loading for 10-hr, 100-hr, FWD, DWD, and litter and DWD combined fuels were not statistically significant for any effects.

Quadrat method

The quadrat based method for litter comparison was the only response variable that presented significant two-way interaction between time and thin effects ($P < 0.05$) (Figure 3-13). Litter biomass consumption was significant for both BNT and BT treatments (3.2 and 2.7 tons per acre, respectively) after the first burning. The fuel recovery after 3 years, however, was significant only for BT, presenting an increment of 2.6 tons per acre of litter. The litter layer after the burning in 2018 was significantly consumed only for BT, reducing 2.2 tons per acre. When analyzing the duff layer, time effect revealed to be significant ($P < 0.01$) (Figure 3-14). After the first burning, the duff layer consumption was not significant, as well as the recovery from 2015 to 2018. After the second burning, the duff biomass significantly reduced comparing to the initial conditions in 2015 (approximately 4.5 tons per acre from pre-burning 2015 to post-burning 2018).

Time effect was significant ($P < 0.01$) for litter and 1-hr fuel combined (Figure 3-15). After the fire in 2015, 3.1 tons per acre of these fuels were consumed, resulting in a significant difference. The recovery from 2015 to 2018 was significant, presenting an increase of 2.6 tons per acre. The litter and 1-hr fuels consumption after the second burning was significant, with an average reduction of 2.5 tons per acre. Considering total fuel loading, time effect was significant for the model ($P < 0.01$). When performing pairwise comparison, the total biomass was significantly consumed after two burnings, with a reduction of 7.8 tons per acre from pre-conditions in 2015 to after the second fire in 2018 (Figure 3-16).

The changes in fuel loading for 1-hr, 10-hr, and FWD fuels were not statistically significant for any effects.

Discussion

The two fuel loading techniques presented some inconsistencies when comparing the results. The quadrat method was shown to be more conservative than the transect method. These dissimilarities can be attributed to the differences in the methods: while the quadrat method is able to quantify the dry weight of the fuels, the transect method considers the depth of litter/duff profile. The compactness of the profile can vary according to environmental conditions, which can influence the accuracy of results (Galgamuwa, 2017). The quadrat method provides more reliable data; however, the advantage of using the transect method is that it allows the collection of 100-hr and 1000-hr fuel class data.

Except for litter biomass measured by the quadrat method, no interaction was found between burning and thinning treatments, and thinning treatment was only significant for 1000-hr sound fuels, which means that implementing the thinning treatment did not have a significant influence on fuel loading and recovery for most fuel classes.

For the quadrat method, the interaction between time and thinning might indicate that at the same time that thinning can increase the litter recovery, the high rates of litter accumulation also can influence the fire behavior, since litter is consumed during the flaming phase (Lutes et al., 2006). The BT plots recorded higher temperatures, and the consumption after the burning in 2018 was significant while it was not for B. The transect method indicated fast litter recovery after 3 fall seasons (2015, 2016 and 2017) and a significant fuel consumption after the second burning, but no differences between B and BT were observed.

In both methods, the first burning did not significantly consume the duff layer, while the second burning presented a statistical difference when compared to the initial conditions. This could be due to duff's higher moisture content and compactness, which resulted in slower consumption during the fire. Moreover, it is consumed in the smoldering phase and associated with fire effects (Ottmar, 2014; Lutes et al., 2006). The fact that litter depth decreased after both burnings while it was not significant for duff can be explained because litter is less densely packed than duff and its consumption is faster.

The increased litter consumption observed is a positive result, as litter reduction post-fire can be beneficial to oak seedling establishment because thick litter layers impede root penetration into soils and can lead to long and weak stems. However, if too much litter is consumed, the acorns are subject to desiccation (Arthur et al., 2012). The overall fuel recovery from 2015 to 2018 before the fire was successful. Duff layer recovery is essential for burning because it acts as a layer of insulation during fire, reducing heat transfer to the soils, which prevents soil nutrient reduction, and microfauna and underground living plant tissue mortality (Lutes et al., 2006). The recovery of the litter layer is important to provide enough fuel to carry out an efficient future burning and accomplish the project's goals.

1-hr (except the first burning when using the transect method), 10-hr, 100-hr and 1000-hr and their combinations into FWD and DWD did not significantly change after the burning treatments, which might mean that the fire intensity was not strong enough to consume these fuels. The significance on 1-hr fuels consumption after the first burning and no difference after the second when using the transect method can be the result of the higher humidity in 2018, since the finer fuels consumption is strongly influenced by relative humidity (Ottmar, 2014). The thinning effect on 1000-hr sound fuels can be explained by the recent selective removal of trees and saplings in 2015 and 2018, which were converted into fuel on the forest floor, showing a difference when compared to natural addition of this fuel class.

This study documented that there was a complete litter recovery to pre-burn levels after 3 growing seasons, which is important if the objective is to conduct periodic fires in the area to encourage oak regeneration.

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Table 3-1: Thinning Prescription in 2018

Compartment	TPA	SapPA	Additional Recommendations
1	25	20	first the non-oak were removed, then oak if needed
3	25	50	primarily cedar, hackberry and hickory were removed
5	25	50	primarily cedar, hackberry and hickory were removed
7	30	20	first the non-oak were removed, then oak if needed
10	5	20	cedar was the priority, then other non-oak species, especially elm saplings
11	40	0	first the non-oak were removed, then oak if needed

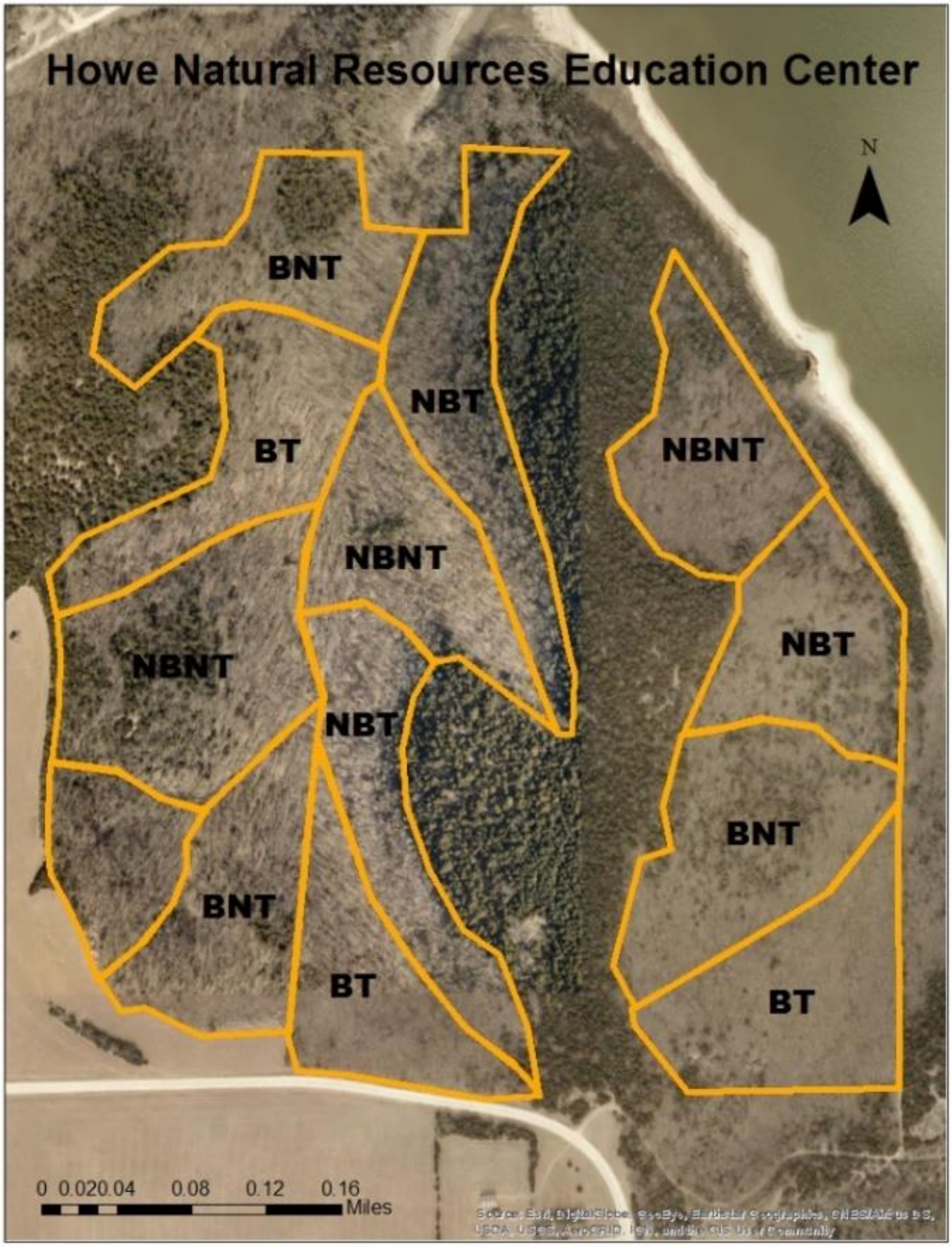

Figure 3-1: Study area and treatment design. NBNT = no-burn and no-thin (control), NBT = no-burn and thin, BNT = burn and no-thin, BT = burn and thin.

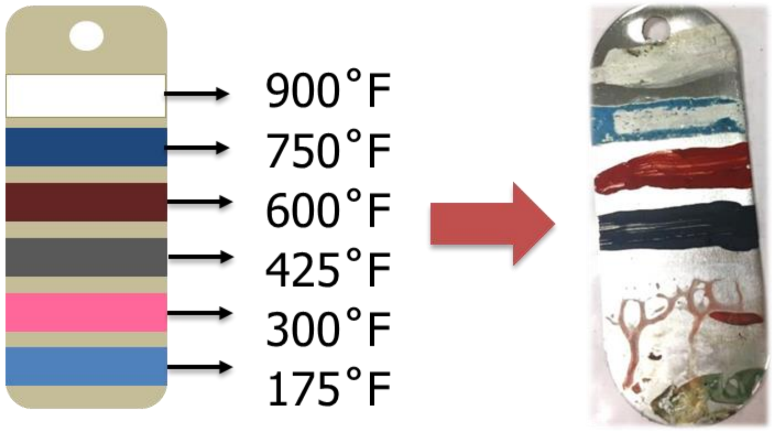

Figure 3-2: Temperatures recorded by the tags

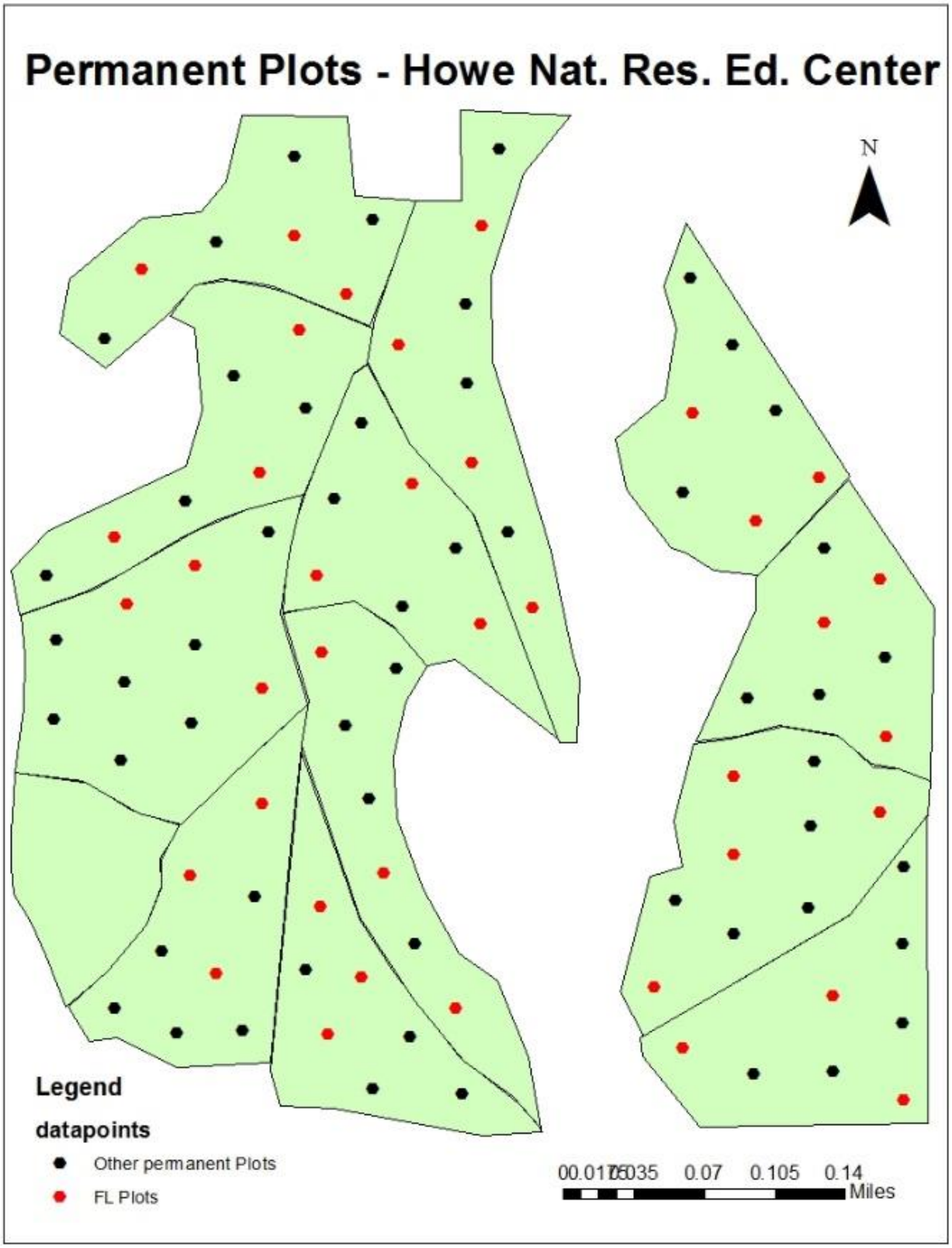

Figure 3-3: FL permanent plots

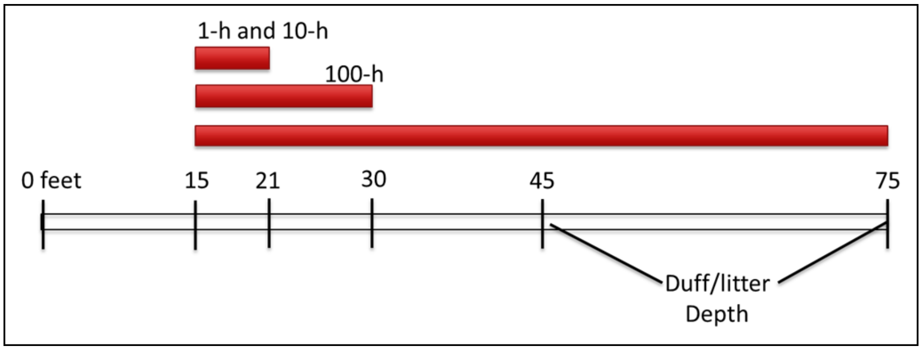

Figure 3-4: Transect for FL data collection, Adapted from Brown (1974)

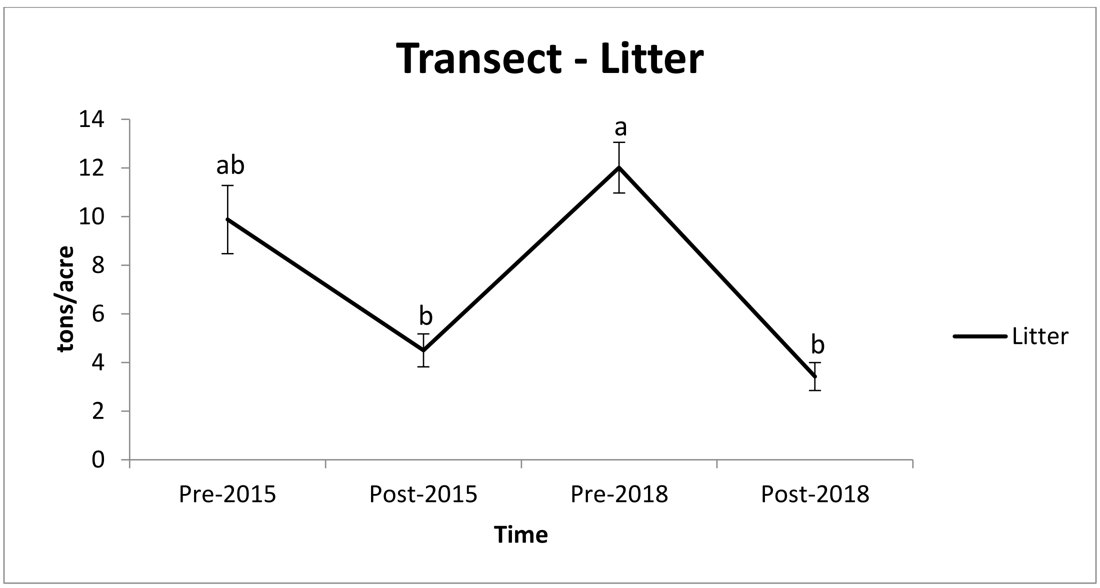

Figure 3-5: Transect method – time effect for litter. Means with the same letter are not significantly different.

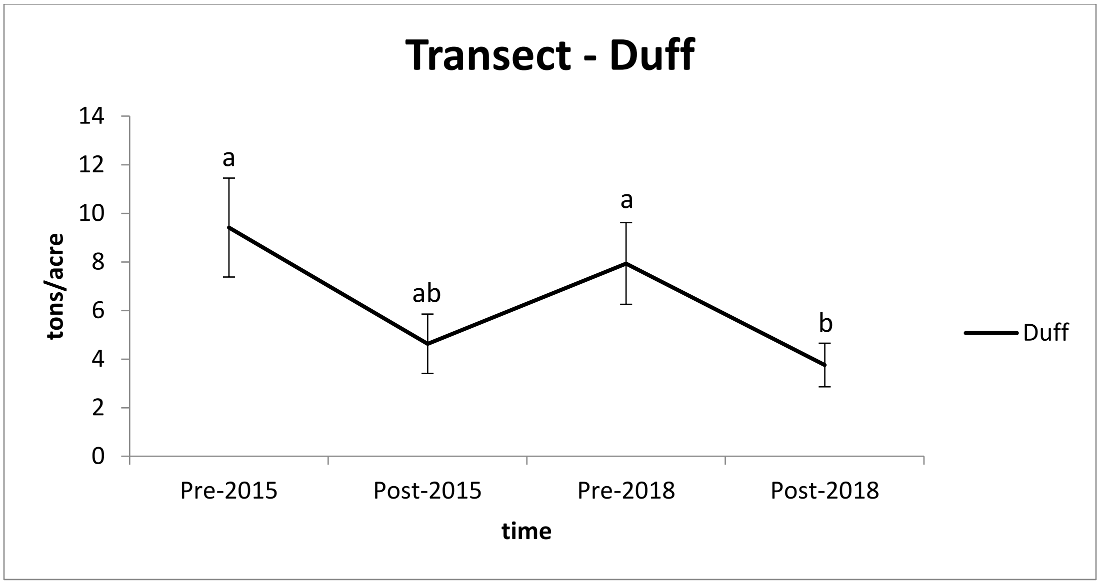

Figure 3-6: Transect method – time effect for duff. Means with the same letter are not significantly different.

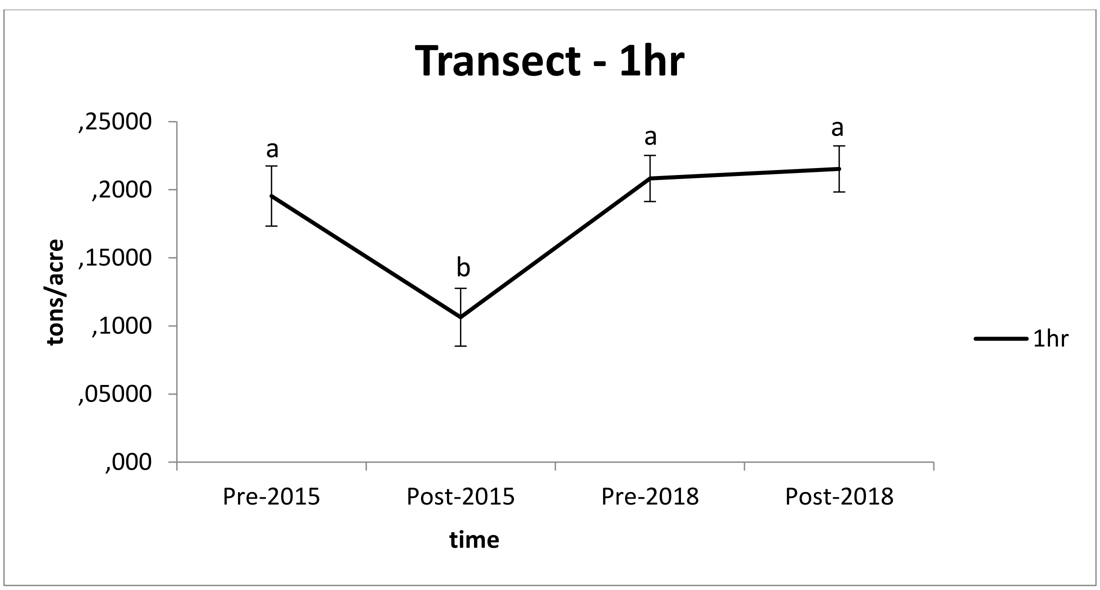

Figure 3-7: Transect method – time effect for 1-hr fuel. Means with the same letter are not significantly different.

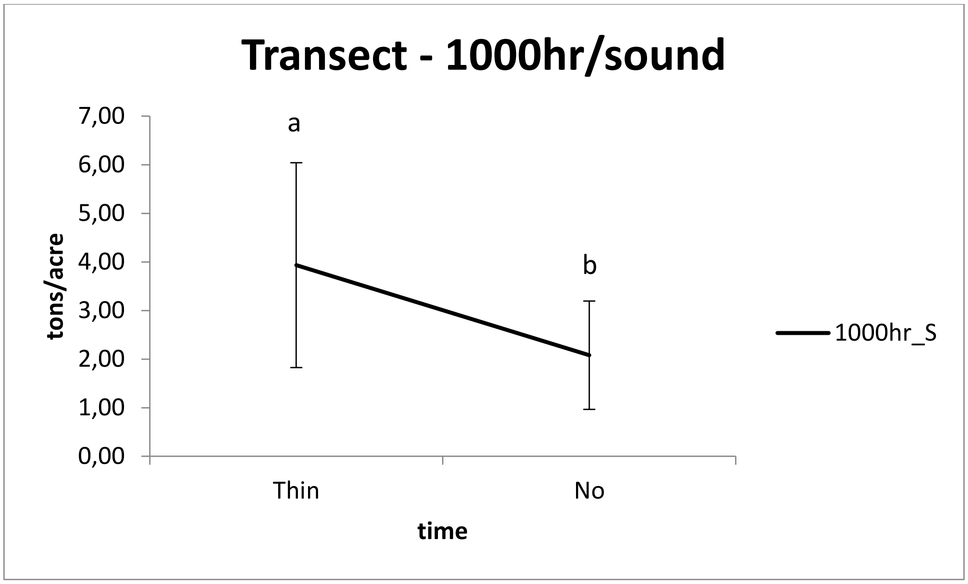

Figure 3-8: Transect method – thin effect for 1000-hr sound fuel. Means with the same letter are not significantly different.

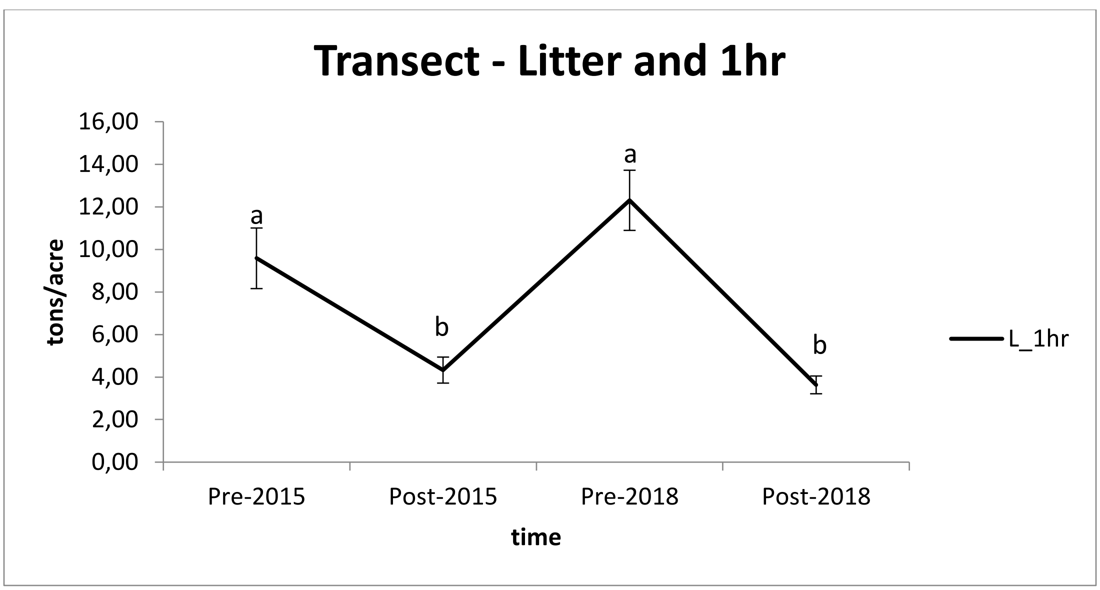

Figure 3-9: Transect method – time effect for litter and 1-hr combined. Means with the same letter are not significantly different.

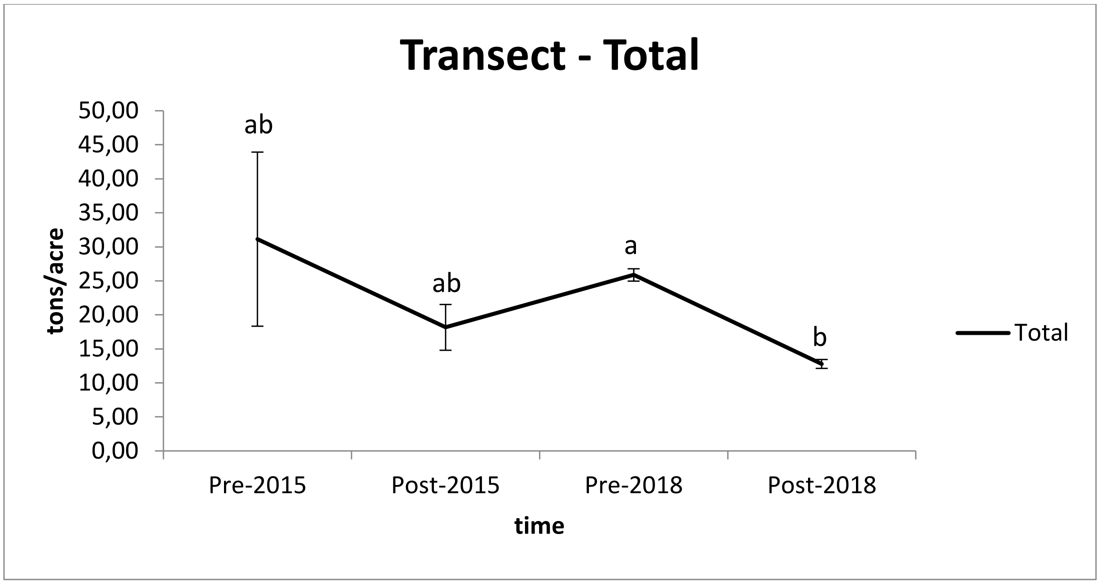

Figure 3-10: Transect method – time effect for litter. Means with the same letter are not significantly different.

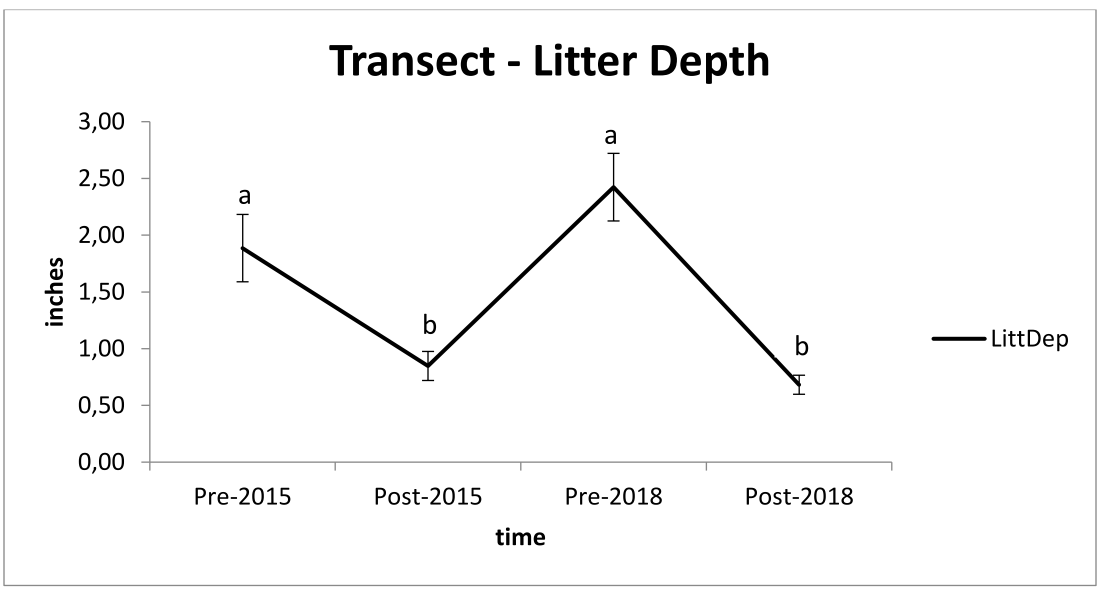

Figure 3-11: Transect method – time effect for litter depth. Means with the same letter are not significantly different.

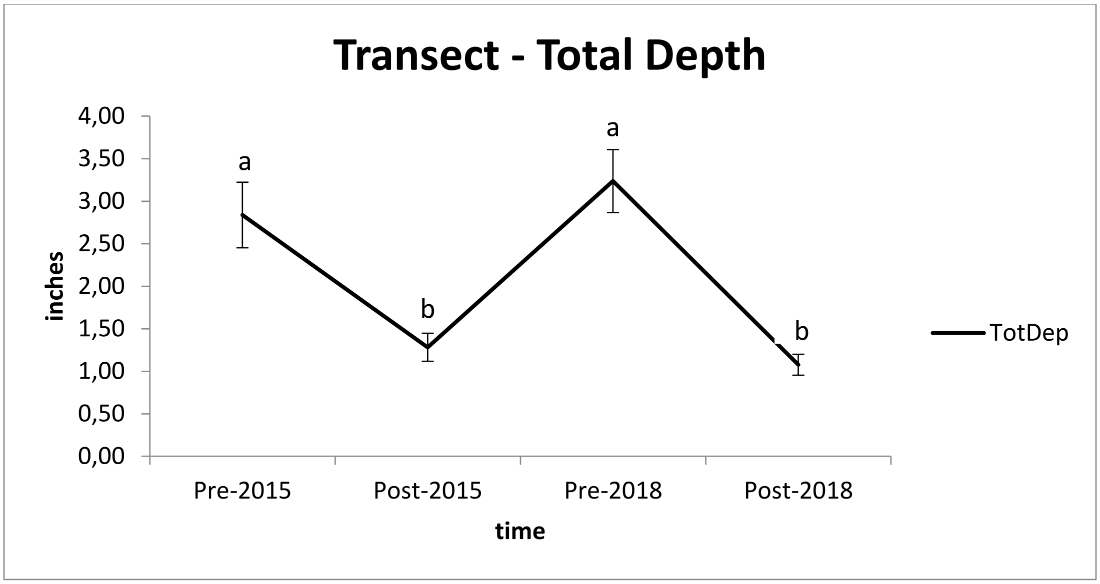

Figure 3-12: Transect method – time effect for total depth. Means with the same letter are not significantly different.

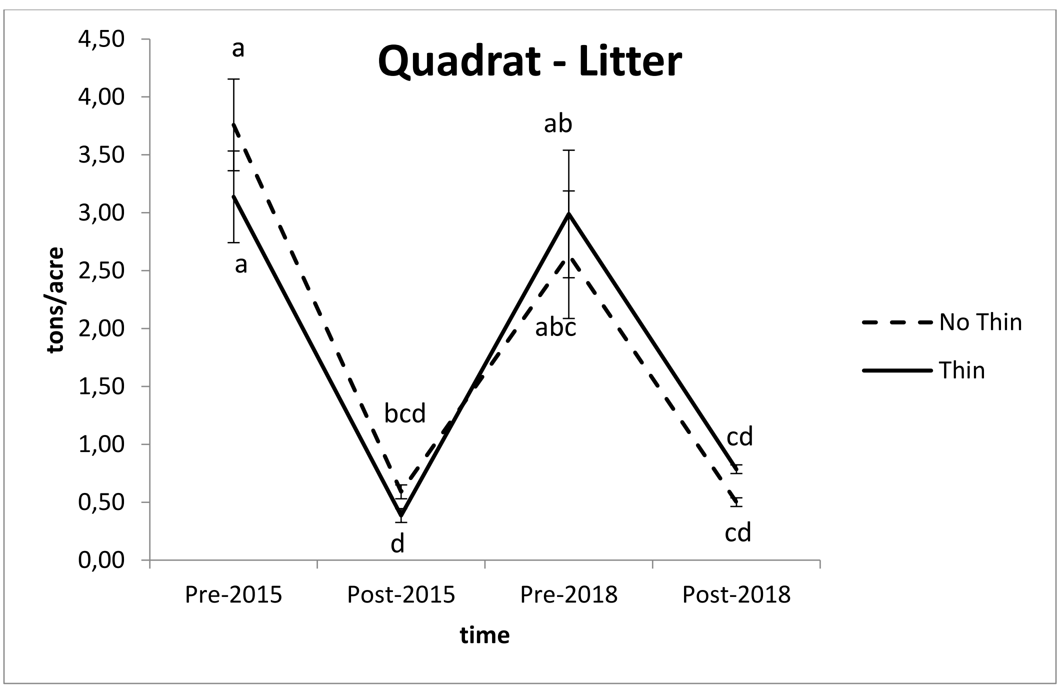

Figure 3-13: Quadrat method – time and thin two-way interaction for litter. Means with the same letter are not significantly different.

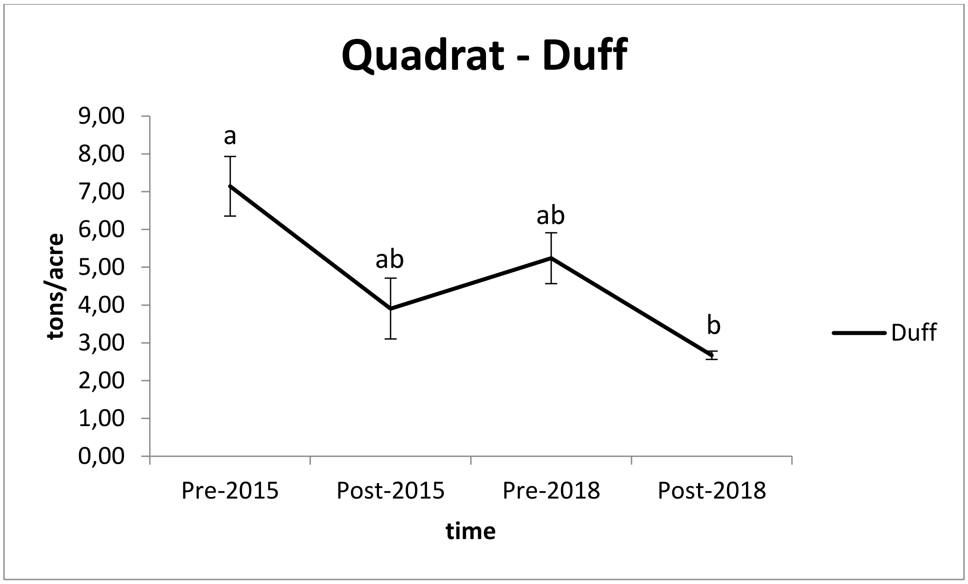

Figure 3-14: Quadrat method – time effect for duff. Means with the same letter are not significantly different.

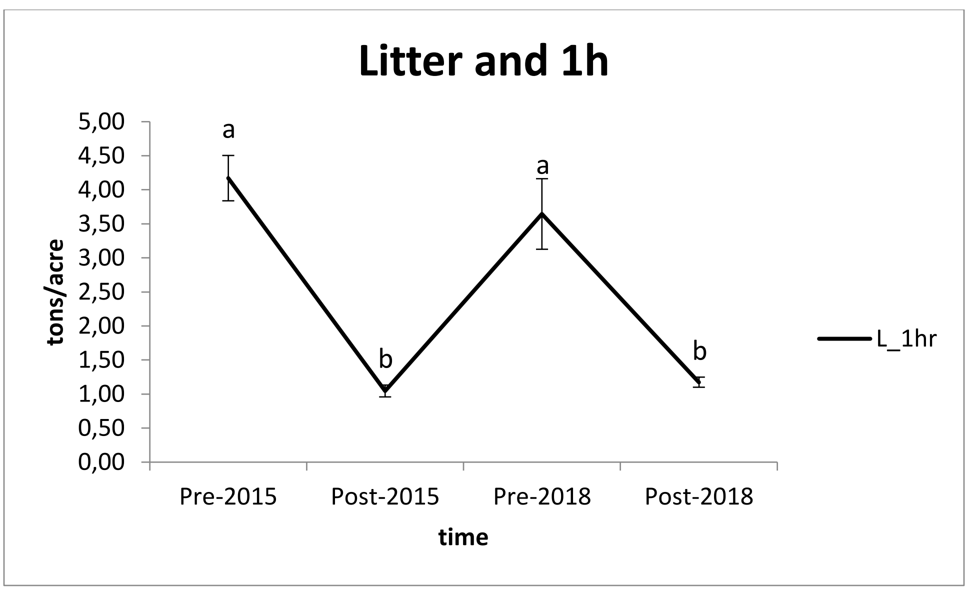

Figure 3-15: Quadrat method – time effect for litter and 1-hr combined. Means with the same letter are not significantly different.

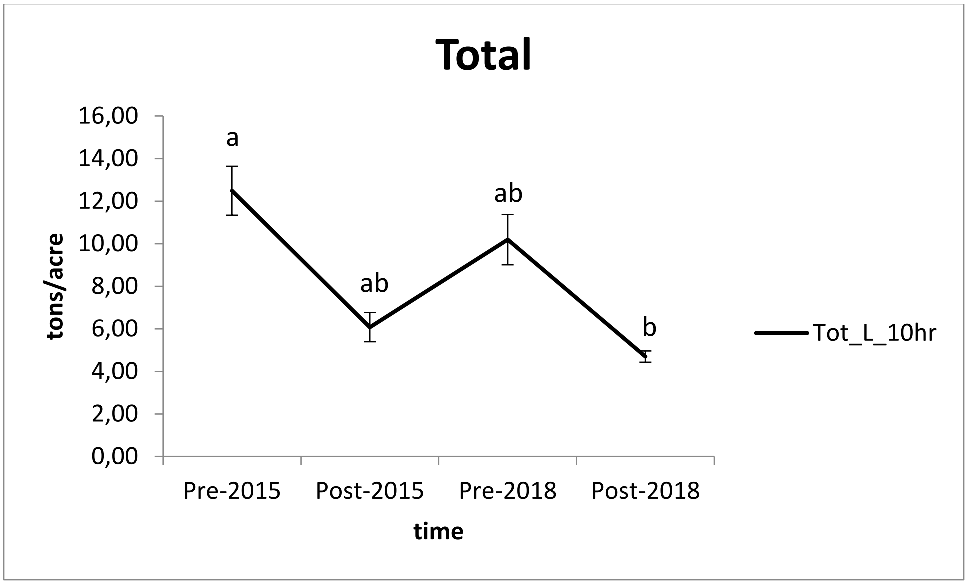

Figure 3-16: Quadrat method – time effect for total. Means with the same letter are not significantly different.

APPENDIX

Field work:

Seedlings inventory


Measuring the DBH

Cleaning the fire break


Transect used for the sampling plane method


Quadrat used to sample fuel loading


Fire ignition


Prescribed burning being conducted


Fire spreading


The big flames were caused when the fire reached a thinned *J. virginiana*


Post burning


Fire break separating burned and unburned areas