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I am submitting herewith a thesis written by William W. DeBord entitled "Effects of Interactions among Two Prescribed Fires, Cover Type, and Canopy Cover on Oak and Red Maple Regeneration in Northern Lower Michigan." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Forestry.

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EFFECTS OF INTERACTIONS AMONG TWO PRESCRIBED FIRES, COVER TYPE, AND CANOPY COVER ON OAK AND RED MAPLE REGENERATION IN NORTHERN LOWER MICHIGAN

A thesis presented for the Master of Science Degree

The University of Tennessee, Knoxville

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ABSTRACT

The process of regenerating oak (*Quercus spp.)* is problematic on most intermediate to high-quality sites throughout the eastern US. Oak is often present in the overstory and abundant in the understory, but is absent from the midstory due to increased competition from less-valuable mesic species such as *Liriodendron tulipifera* and *Acer rubrum*. Red maple has expanded its range dramatically since fire suppression began in the 1930s, and is an important competitor of oak. To study relationships between oak and silvicultural treatments, an experiment was initiated in 1990 that included three northern red oak (*Quercus rubra*)-dominated stands and three red pine (*Pinus resinosa*) plantations in northern Lower Michigan. Areas of each stand were thinned to four levels of canopy cover in 1991: clearcut, 25% residual canopy, 75% residual canopy, and uncut control, with caged and uncaged northern red oak seedlings planted within each treatment. A thick midstory of red maple developed over the subsequent ten years, hindering development of advance oak regeneration. Low-intensity, early-spring prescribed fires were conducted on all stands in 2002 and 2008 in an effort to control red maple. Heights of planted red oak and naturally occurring red maple and oak regeneration in three size classes were measured before and after each fire with the objectives to: 1) Test the hypothesis that oak sprouts would have greater height growth after the 2008 prescribed burn than after the 2002 prescribed burn; 2) Test the hypotheses that (a) red maple stems would be reduced to a greater degree following the 2008 burn than following the 2002 burn, and that (b) the number of natural oak stems would be increased to a greater degree following the 2008 burn than following the 2002 burn; and 3) Evaluate the relationships between post-burn planted oak sprout height and pre-burn planted oak sprout height, fire temperature, and canopy cover. Following the second fire, planted oak sprouts increased in height rapidly in pine stands, where there was little red maple competition, but grew less rapidly in oak stands. Red maple densities decreased more following the first fire than the second fire. The hypothesis that natural oak regeneration stem densities would increase to a greater degree following the 2008 burn than following the 2007 burn was not supported. Pre-burn planted oak height was the best predictor of post-burn planted oak height.

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INTRODUCTION

Importance of Oak

Oak (*Quercus*) species are important not only for timber, but also because they produce nutrient rich hard mast, which is consumed by a variety of birds and mammals (McShea et al., 2007). Oak has been deemed a foundation species because of its direct and indirect influences on ecosystem processes and community dynamics (Ellison et al., 2005; McShea et al., 2007). Fralish (2004) classified oak species as keystone species because of their cascading effects on wildlife. Oak species have maintained an important role in eastern United States forests for the last 8,000 years (Foster et al., 2002). Changes in land use and disturbance regimes brought on by European settlement helped oak persist and expand its range through the 1800s. Mixed-oak forests persist as the predominant forest type in present day eastern forests, but very little oak recruitment into the overstory has occurred since the early 1900s (Abrams, 1992; Brose et al., 1999a).

Fire and Oak

The hypothesis that periodic fire is important in perpetuating oak in eastern forests has gained prominence in recent years. A common explanation for current problems with oak regeneration is an increase in competitor abundance and a decrease in understory light resulting from the advent and advancement of fire suppression practices over the last 70+ years (Abrams, 1992). Dendrochronological studies of fire scars in old-growth forests indicate fire return intervals of 4-20 years prior to European settlement, and that widespread fires were frequent during, or just prior to, the establishment of current oak overstories (Dey and Guyette, 2000;

Shumway et al., 2001; Abrams, 2005; McEwan et al., 2007). Witness trees in southern Ohio indicate the median fire return interval was less than five years in local forests until effective fire suppression began in 1932 (McCarthy et al., 2001; Sutherland and Hutchinson, 2003; Albrecht and McCarthy, 2006). Oak-pine forests in northern Lower Michigan had a mean fire return interval of 9 years from 1870 to 1920, during the height of the logging era (Whitney, 1987).

Fire History

Native Americans used fire extensively to manipulate the landscape for numerous reasons, including hunting ground preparation, berry production, travel, communication, warfare, land-clearing, and agriculture (Abrams, 1992; Lorimer et al., 1994; Delcourt and Delcourt, 1997). These activities increased as Native American populations grew and expanded throughout the East (Abrams, 1992). European settlers adopted Native American burn techniques that, when implemented on a larger scale along with frequent partial harvests, created a gap-fire disturbance regime that likely played an important role in the creation and maintenance of present day oak-dominated forests (Abrams, 1992; Brose et al., 1999b).

Vast forests of eastern white pine (*Pinus strobus*) were lost to extensive logging, land clearing for agriculture, and repeated catastrophic fires (Abrams, 1992; Whitney, 1987), and the introduction of exotic insects and diseases, such as chestnut blight, which facilitated the loss of the once dominant American chestnut (*Castanea dentata*), drastically changed disturbance regimes in eastern forests (Abrams, 1992, 1998; Brose et al., 2001). These disturbances created large canopy openings, which increased down woody debris, elevated fuel loads, increased amounts of sunlight on the forest floor, and facilitated air movement, all of which increased the likelihood of moderately intense fires suggested to favor oak species (Myers and Van Lear, 1998; Ellsworth and McComb, 2003). The frequent, large-scale disturbance patterns of widespread clearcutting followed by moderately intense fire associated with the logging and charcoal industries in the 19^{th} and early-20^{th} centuries promoted oak species to expand their abundance on the landscape and establish the mixed-oak forest type that presently dominates eastern forests (Albrecht and McCarthy, 2006; Lorimer, 1993; Guyette et al., 2002).

The cycle of fire and oak recruitment in upland forests that likely went on for thousands of years, and had intensified in the late 19^{th} and early 20^{th} centuries, was broken in the 1930s with the implementation of widespread fire suppression (Abrams, 2005). Oak species in mesic upland forests are not self-replacing in the absence of fire and other canopy-reducing disturbances, and forests may progress through succession toward systems dominated by more mesophytic species (Abrams, 1992, 1998; Arthur et al., 1998; Taylor and Lorimer, 2003).

Absence of Fire

Many mixed-oak forests in the eastern US have entered the understory reinitiation stage of development and contain dense understories of red maple and other shade tolerant species (Abrams, 1998; Albrecht and McCarthy, 2006; Arthur et al., 1998). Stands left undisturbed for decades develop stratified layers of shade-tolerant species beneath the canopy that can limit understory light levels to 1-3% above canopy photosynthetically active radiation (PAR) (Lorimer et al., 1994; Miller et al., 2004; Aldrich et al., 2005). Dense understory shade is the primary obstacle limiting growth and survival of oak seedlings and sprouts (Lorimer et al., 1994). Oak seedlings have a tendency to divert much of their photosynthate to root growth over stem growth (Crow, 1988). Large root systems and intermediate shade tolerance allow upland oaks to persist in a seedling-sprout stage, where they repeatedly die back and resprout in low light conditions

(Crow, 1988; Lorimer, 1993). Oak has a relatively non-plastic growth strategy, which limits its ability to capture transitory increases in light and its ability to take advantage of gaps in the canopy created by fallen trees (Johnson et al., 2002). Dillaway and Stringer (2007) suggest that white oak (*Quercus alba*) seedlings suppressed in the understory for prolonged periods may lose the ability to grow vigorously in response to increased light from canopy disturbances. They found that oaks with root systems > 8 years old did not exhibit rapid height growth following release. As a result, oak advanced regeneration is often underrepresented in the midstory, even though oak seedlings may be abundant in the understory (McCarthy et al., 1987, 2001a; Arthur et al., 1998).

Oak Regeneration Problem

Today, land managers face considerable difficulty regenerating mixed-oak stands throughout eastern North America, especially on mesic upland sites (Crow, 1988; Loftis and McGee, 1993; Rogers et al., 1993). Oak species remain prevalent in the overstory and oak seedlings are abundant in the understory of many eastern forests, but large advanced oak regeneration has become rare on all but the most xeric and nutrient-poor sites. On high-quality and some intermediate-quality sites, advanced oak regeneration is being overtopped and replaced in the midstory by more mesic, shade-tolerant species (Abrams and Nowacki, 1992; Abrams, 1998). The largest increase in competitor species frequency on upland oak sites in much of the eastern U.S. is from red maple (*Acer rubrum)* (Abrams, 1998, 2005). The development of oak-dominated forests into systems dominated by more mesophytic species has been documented in several studies across eastern North America (Crow, 1988; Abrams, 1992, 1998; Lorimer, 1993; Iverson et al., 2008).

Shelterwood

Historically, canopy openings of varying extent were caused by natural disturbances such as insect outbreaks, passenger pigeon activity, ice storms, wind events, or fire throughout eastern hardwood forests (Loftis, 1990). Loftis (1990) developed a shelterwood method of regenerating northern red oak (*Quercus rubra*) in the southern Appalachians, where yellow-poplar (*Liriodendron tulipifera*) is the major competitor of oak, as a means mimicking these natural openings.

The shelterwood method is generally defined as a series of partial cuts that mimic moderate canopy disturbances, releasing a desired amount of light to the understory, and thus encouraging development of advanced oak regeneration (Loftis, 1990; Johnson et al., 2002). The canopy of an existing stand is cut to a specified residual basal area dependent on site productivity, which is designed to give desired regeneration ample light and time to establish and develop into a competitive size. The canopy is removed following several years of development, resulting in a new even-aged stand (Loftis, 1990).

Shelterwood Limitations

Oak stands on intermediate and mesic sites often develop excessive woody competition following partial harvests. Competitor species in a given eastern hardwood stand depend on a suite of factors including, but not limited to, eco-region, climate, geography, and site productivity. Measures are often required to control midstory and understory competition to ensure an oak component is present in the new stand (Brose, 2008). The three general methods for controlling understory competitors are chemical treatments, mechanical treatments, and prescribed burning. Loftis (1990) demonstrated the efficacy of herbicides applied to midstory competition prior to an oak shelterwood treatment on high-quality sites in the southern Appalachians. However, negative public opinion and increased bans on herbicide use in some regions limit chemical treatments as a viable option. Mechanical thinning of competitors can effectively promote desired stems, but is labor-intensive and costly and may have to be repeated to control sprouts that develop following the initial treatment.

Fire and Shelterwood

Prescribed fire following shelterwood cuttings can be effective at reducing the density of advanced regeneration of competitors relative to that of oak (Brose and Van Lear, 1998; Brose et al., 1999a). Larger root systems and greater below-ground buds capable of producing sprouts when top-killed give oak species an advantage over other woody competitors following fire (Brose and Van Lear, 1998, 1999; Brose, 2008). Brose and Van Lear (1998) found the most effective control of yellow-poplar was achieved with spring and summer burns when carbohydrate reserves in the rootstocks are low and fire intensities tend to be higher. Burns of lower intensity present less potential hazard, but several low-intensity burns may be necessary to achieve the same results as a single, high-intensity burn (Loftis, 1990; Brose and Van Lear, 1998, 1999).

Dormant season prescribed burning in thinned, mature Central Hardwood Forest stands in southern Ohio were found to be largely ineffective in controlling oak competitors 4-years after treatment (Albrecht and McCarthy, 2006). The Albrecht and McCarthy (2006) study involved thinning treatments to reduce basal area by 20-30% followed by a dormant season prescribed burn the same year. The single burn initially reduced the abundance of red maple regeneration in the understory, but it recovered to pre-treatment levels by the end of the study by seeding in from surrounding areas and resprouting from top-killed saplings (Albrecht and McCarthy, 2006). Although competition was reduced in the short-term, oak regeneration <140 cm in height was not released from suppression and growth rates did not increase following treatments. Albrecht and McCarthy (2006) concluded that prescribed fire may be more effective several years after thinning, and additional fires may be needed to control the strong resprouting of red maple and other fast-growing early successional species.

Arthur et al. (1998) found that single and repeated fires in upland oak-pine forests in Kentucky reduced the density of red maple while simultaneously promoting multiple sprouts from surviving red maple. Chestnut oak (*Quercus montana*) sprouts were not reduced by fire, but did not gain any height advantage over red maple sprouts (Arthur et al., 1998).

Iverson et al. (2008) documented the effects of thinning and multiple burns on natural oak and hickory regeneration in mature stands across a moisture gradient in southern Ohio. Stands were thinned in 2000 and prescribed burns were implemented in 2001 and 2005. Oak and hickory advanced regeneration (> 50 cm tall) increased on drier sites following thin and burn treatments, but were unresponsive on mesic sites following the same treatments (Iverson et al., 2008). The second fire (2005) reduced densities of red maple and yellow-poplar, which had increased following the first fire four years earlier. The second fire also burned at a higher-intensity, causing moderate overstory mortality, which stimulated growth in oak (Iverson, et al., 2008). These results suggest partial harvesting followed by repeated fire is a promising strategy for managing oak on xeric and intermediate sites in the Central Hardwoods Region.

Post-fire survival increased in oak roots with a root collar diameter (RCD) of > 6.4 mm (Brose and Van Lear, 2004). Brose (2008) monitored RCD of oak seedlings across stages of a three step shelterwood sequence (uncut, preparatory cut, first removal cut, and final cut) designed to optimize root development, and to determine how long to wait between thinning and prescribed fire to ensure oak RCD development into size ≥ 6.4 mm in northern Pennsylvania. Harvests reducing canopy cover to ≤ 50% were likely to produce oak stems with the desired (≥ 6.4 mm) RCDs (Brose, 2008). Cuts leaving ≥ 50% cover were less likely to produce desired growth in roots, and were advised against when burning, because they slowed root development and decreased the ability of oak seedlings to withstand fire (Brose, 2008). Prescribed burns 4-7 years following the first removal cut (50% removal) were recommended, depending on the dominant oak species (Brose, 2008). This interval also gives logging slash adequate time to decompose, reducing the intensity of potentially hazardous fires.

The shelterwood-burn technique has been successful in controlling yellow-poplar competition on productive sites (Brose et al., 1999a, 1999b, 2001), however, red maple was not a major competitor of oak on their study sites. Brose et al. (1998, 1999a, 2001) did mention red maple stump sprouts in the understory following prescribed fire, but, because red maple is susceptible to disease, did not predict these stump sprouts would compete with oak regeneration. Other studies in which multiple prescribed fires were used to promote oak regeneration on sites where red maple is a significant competitor have been conducted under mature mixed-hardwood canopies (Arthur et al., 1998; Gilbert et al., 2003; Alexander et al., 2008), have implemented dormant season prescribed burns (Albrecht and McCarthy, 2006), or have incorporated only one level of canopy cover (Iverson et al., 2008). Our study tested the effects of two growing season prescribed fires across four levels of canopy cover on sites where red maple is the primary competitor of oak. To our knowledge, no one has tested the shelterwood-burn technique in Michigan, or tested the effects of prescribed fire on oak and its competitors in pine stands.

Long-term data are required to arrive at definitive results from regeneration studies, and the number of replicated oak regeneration studies followed beyond 1-5 years is limited. Buckley et al. (1998) initiated an oak regeneration study on oak and pine sites in northern Lower Michigan in 1990 and the survival and growth of all seedlings have been periodically documented from time of planting to the present.

The overall plot layout and experimental design were developed and implemented in 1990 and 1991 by Buckley et al. (1998) with two main objectives. The first was to test the hypothesis that regeneration of northern red oak is more successful in pine stands than in oak stands. The second objective was to test whether removal of potential overstory and understory competitors increased the success of oak regeneration on moderately productive sites. Beneficial effects of competitor removal were evident by 1992, but important effects of browsing and frost damage were also very apparent. A comparison of burned and unburned areas was desired by the investigators in 1990, but prescribed fire was not incorporated into the study due to a lack of Michigan Department of Natural Resources (DNR) personnel, funding to conduct the burns, and a negative public image of burning in the region.

Monitoring of treatment effects continued 1992-2000, and the development of heavy red maple competition in certain treatments led to additional research by Hartman et al. (2005). This follow-up study had three objectives: 1) To test a modification of the shelterwood-burn technique forwarded by Brose et al. (2001) and the hypothesis that a prescribed burn would reduce the abundance and cover of red maple and other oak competitors; 2) To test the hypothesis that planted oak seedling pre-burn height and/or basal diameter could be used to predict post-burn sprout height growth; and 3) To investigate interactions among a prescribed burn and forest cover type (oak vs. pine), canopy cover, and browsing on growth, density, and survival of both oak regeneration and its competitors. As expected, the burns in pine stands were more intense than in the oak stands, and burn intensity was greater in the treatments with greater canopy cover and associated litter. Reasonable relationships were found between pre-burn size measures and post-burn oak sprout growth. A large proportion of the oak stems planted in 1991 that were alive just prior to the burn resprouted, but browsing damage to oak sprouts that were not protected from browsing was very heavy. Red maple stem densities were clearly set back by the fire, and some larger stems developed fungal infections. Many red maple stems recovered, however, and densities of red maple and oak stems in various size classes in 2006 differed little from densities present prior to the burn. A second prescribed burn was implemented in all treatments in 2008. The research in this thesis will complement objectives addressed in these two previous, sequential studies conducted on sites in northern Lower Michigan.

OBJECTIVES

This study was undertaken to examine the effects of a second prescribed fire on oak and red maple regeneration across four levels of canopy cover 19 growing seasons after initial overstory treatment implementation. Specific objectives were to:

1) Test the hypothesis that planted oak sprouts would have greater height after the 2008 prescribed burn than after the 2002 prescribed burn.

2) Test the hypotheses that (a) red maple stems would be reduced to a greater degree following the 2008 burn than following the 2002 burn; and (b) the density of oak stems would be increased to a greater degree following the 2008 burn than following the 2002 burn.

3) Evaluate relationships between post-burn planted oak sprout height and pre-burn planted oak sprout height, fire temperature, and canopy cover.

METHODS

Site Description

Second-growth natural oak stands and unthinned red pine plantations on state forest land were selected as study sites in southern Crawford County (84˚45'W, 44˚31' N, elevation 400 m) and southern Roscommon County (84˚41' W, 44˚14' N, elevation **3**00 m), Michigan, USA. Both counties are within the Grayling Outwash Plain of the Highplains District of the northern Lower Peninsula (Albert, 1995). All stands occurred on sandy, mixed, frigid, Alfic Haplorthods developed in pitted outwash, and soil physical and chemical properties among stands were comparable (Kim et al. 1996). All sites were designated as moderately productive (Kim et al. 1996). Slopes were ≤ 5%. Site indexes for both northern red oak and red pine in the Lakes States region were 17-18 m (base age 50) (Carmean et al., 1989; Kim et al., 1996). Red pine plantations were selected because, at the time the study was implemented, natural pine stands of sufficient size and density no longer existed in the area. Tree ring counts on stumps, following canopy treatment in 1991, indicated the oak stands were 88-100 years old, and pine plantations were 59-75 years old (Buckley et al., 1998).

Prior to European settlement, Crawford and Roscommon counties were covered with extensive eastern white pine (*Pinus strobus*), red pine (*Pinus resinosa*), and jack pine (*Pinus banksiana*) forests, along with oak-pine and northern hardwood stands (Whitney, 1987). Analysis of pre-logging overstory species composition for these sites indicated: 41% red pine, 19% white pine, 18% jack pine, 13% *Quercus* spp., 5% *Populus* spp., and 0.4% red maple (Whitney, 1987). By 2001, forest types throughout Michigan had converted to: 37%

maple/beech/birch, 18% aspen/birch, 14% spruce/fir, 11% oak/hickory, 10% white/red/jack pine, 9% elm/ash/cottonwood, and 1% other softwoods (Leatherberry and Brand, 2003).

Experimental Design

Natural oak stands and red pine plantations were each divided into three replicate blocks measuring 1.74 ha. Each of the six blocks was subdivided into four square plots measuring 66 x 66 m (0.44 ha each). Each plot randomly received one of four canopy cover treatments: clearcut (CC), 25% residual canopy (25%), 75% residual canopy (75%), or uncut control (UC) (Fig. 1). The minimum distance from a treated area to a road was at least 20 m for all stands. Plots receiving partial canopy cover treatments were thinned from below by removing subcanopy trees >2.54 cm dbh first, followed by the removal of canopy trees as needed. Red maple and red pine in subordinate canopy positions were cut first. All stems ≥ 2.54 cm dbh were removed in clearcut treatments. All stands were cut between fall 1990 and early spring 1991. Additional stems were removed in winter 1991-1992 in 25%-cover plots to achieve the prescribed canopy cover. Logs were removed with rubber-tired forwarders, or were cut, split, and removed with a medium duty truck. Logging equipment was operated over the same pathways in buffer zones to minimize soil compaction and understory disturbance whenever possible.

Four understory treatment subplots measuring 15 x 15 m (0.02 ha each) were arranged in a square at the center of each canopy treatment plot (Fig. 1). Understory treatments randomly assigned within each canopy treatment were: Shrub Layer Removal (S) (herbs, shrubs, and saplings > 25 cm tall up to stems of saplings 2.54 cm dbh), Herb Layer Removal (H) (herbs, shrubs, and seedlings < 25 cm tall), Litter Removal down to humus layer (L), and Control (C)

(Fig. 1). This arrangement reduced edge effects by creating an 18 m buffer between understory treatment plots and the adjoining edges of canopy treatment plots (Fig. 1).

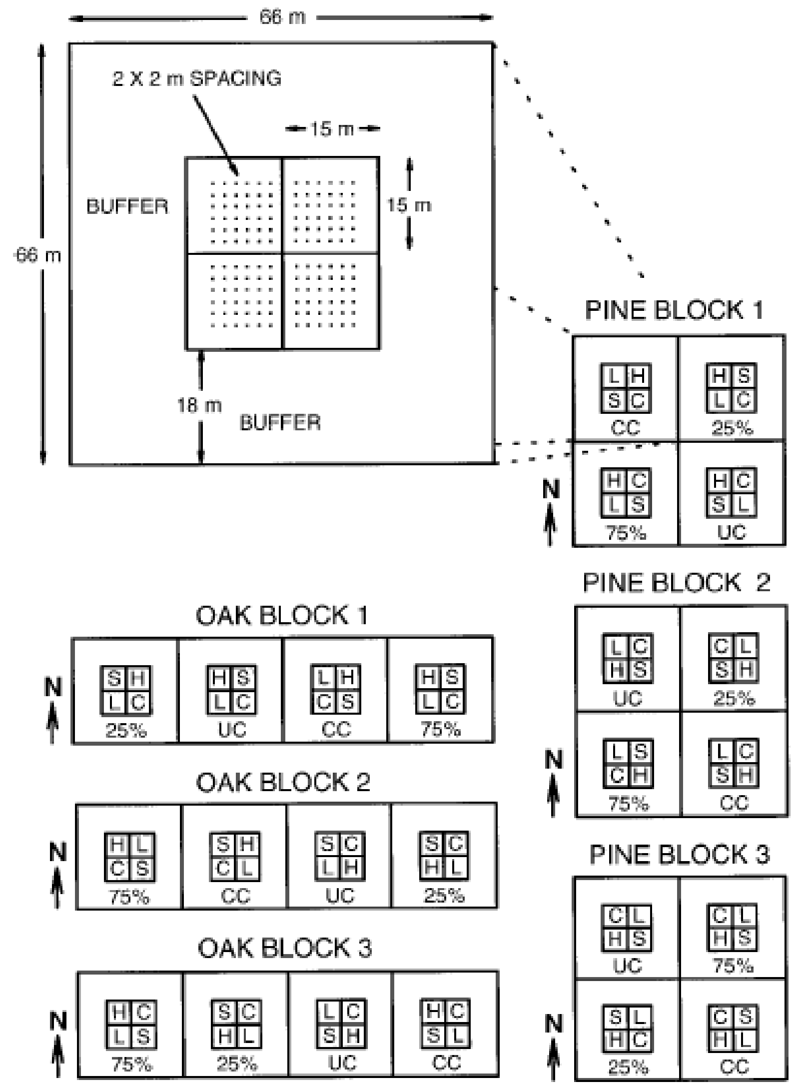

Figure 1. Experimental design (Buckley et al., 1998), northern Lower Michigan, USA: planting locations, buffer zones, understory treatment plots, and canopy cover treatment plots (to scale) within replicate oak and pine blocks. True spatial relationships between replicate blocks have been altered for the purpose of efficient presentation although shape and orientation of blocks are correct. For canopy cover treatments, CC = clearcut, 25% = 25% canopy cover, 75% = 75% canopy cover, UC = uncut control. For understory treatments, C = control, L = litter removal, H = herb removal, and S = shrub removal.

Logging slash was carried out of understory treatment plots by hand prior to understory manipulation. Herb- and Shrub-layer removal treatments were accomplished by hand over the entire 15 m x 15 m plot where assigned. Understory treatments were completed prior to planting, and maintained intermittently between 1992 and 2001.

Acorns and nursery seedlings were originally planted to compare treatment effects on individuals of different age and size (Buckley et al., 1998). Acorns and seedlings were randomly planted at 3,072 total locations, 32 of 36 possible locations within each understory subplot, in 1991. Permanent cylindrical chicken-wire cages, measuring 0.45 m in diameter x 1.83 m in height, were constructed around all seedlings in 1991 to prevent browsing. Cages were replaced in April 2008.

Fire Parameters

Pre-burn planning indicated fire treatments could not be applied under identical burning conditions on all sites due to varying precipitation between sites and excluded wind directions for certain sites. Average relative humidity and wind speeds were nearly uniform for all sites, however, when the fire treatments were applied. The goal of both the 2002 prescribed fire (Fire 1) and 2008 prescribed fire (Fire 2) was to achieve strip-head fires with 0.9 m flame lengths, so as to top-kill all oak seedlings along with its competitors on all six sites.

Oak stands were burned May 15, 2002. The nearest weather station received 0.15 cm of precipitation two days prior to burning. On-site dry bulb temperature was 18°C with 34% average relative humidity (RH). Weather station wind speed was 16 km/h, but mid-flame wind speed averaged only 1.6 km/h. The combination of southwesterly winds and a north-facing slope retarded effective wind speed on oak sites.

Oak stands were burned the second time on May 16, 2008. The nearest weather station received 0.13 cm of precipitation the day of the burn. Weather station temperatures averaged 19°C with 35% average RH. Winds were from the west at 11.2 km/h.

Pine stands were burned on May 21, 2002. The nearest weather station to pine sites 1 and 2 received 0.23 cm of precipitation eight days prior to burning. On-site dry bulb temperature averaged 12°C with 42% average RH. Mid-flame wind speed was from the north-northwest and averaged 2.1 km/h. Pine site 3 received 0.13 cm of precipitation five days prior to burning. On-site dry bulb temperature averaged 11°C with 37% average RH. Mid-flame wind speeds for pine site 3 were from the west and averaged 2.6 km/h.

Pine stands were burned the second time on May 13, 2008. The weather station nearest to pine sites 1 and 2 received 2.5 cm of precipitation five days prior to burning. Weather station temperature averaged 18°C with 41% average RH. Weather station wind speed was 11.2 km/h from the south. On-site dry bulb temperature averaged 19˚C with average relative humidity 45%. On-site winds were from the south-southeast at 6.4 km/h.

Measurements

Temperature indicating paints (Temqilaq Paints, B.J. Wolfe Enterprises Inc.) were used to quantify field measurements of fire temperature. Eight separate paints calibrated to liquefy at 79°, 149°, 204°, 260°, 316°, 371°, 593°, and 816°C were painted onto ceramic tiles mounted on steel rods face down 0.6 m above the soil surface in the center of each understory treatment plot.

Percent canopy cover was measured with a spherical densiometer. Four densiometer measurements were taken in each of the four cardinal directions at understory treatment plot-center (Fig. 2). Measurements were averaged to attain percent canopy cover for each understory treatment.

Planted oak seedlings were measured in 2000, 2003, 2006, and 2009 at the end of the growing season in late-July/early-August. Total height was recorded to the nearest centimeter for the tallest stem on each planted oak seedling. Total number of stems was also recorded to determine growth and sprouting capability of various oak size classes. Basal diameter was measured 10 cm above ground to the nearest millimeter using Vernier calipers. Evidence of deer browsing, frost damage, stem dieback, mechanical damage, and insect defoliation were noted for each planted oak seedling.

Natural regeneration was measured in late-July/early-August of 2001, 2003, 2006, and 2009. Genets of woody stems were tallied by species into three size-classes: (Small) stems < 25 cm height, (Medium) stems ≥ 25 cm tall and < 2.54 cm diameter, and (Large) ≥ 2.54 cm diameter and <10 cm diameter. Small size-class stems were measured within 1 m-square quadrats (Fig. 2). Medium size-class stems were measured within 2 m diameter circular plots (Fig. 2). Large size-class stems were measured within 4 m diameter circular plots (Fig. 2). Four sampling locations were placed within each 15 x 15 meter subplot centered at planting locations 8, 11, 26, and 29 (Fig. 2). Smaller sampling plots were nested within larger plots. Stems of red and white oak regeneration were pooled into a single category for analysis.

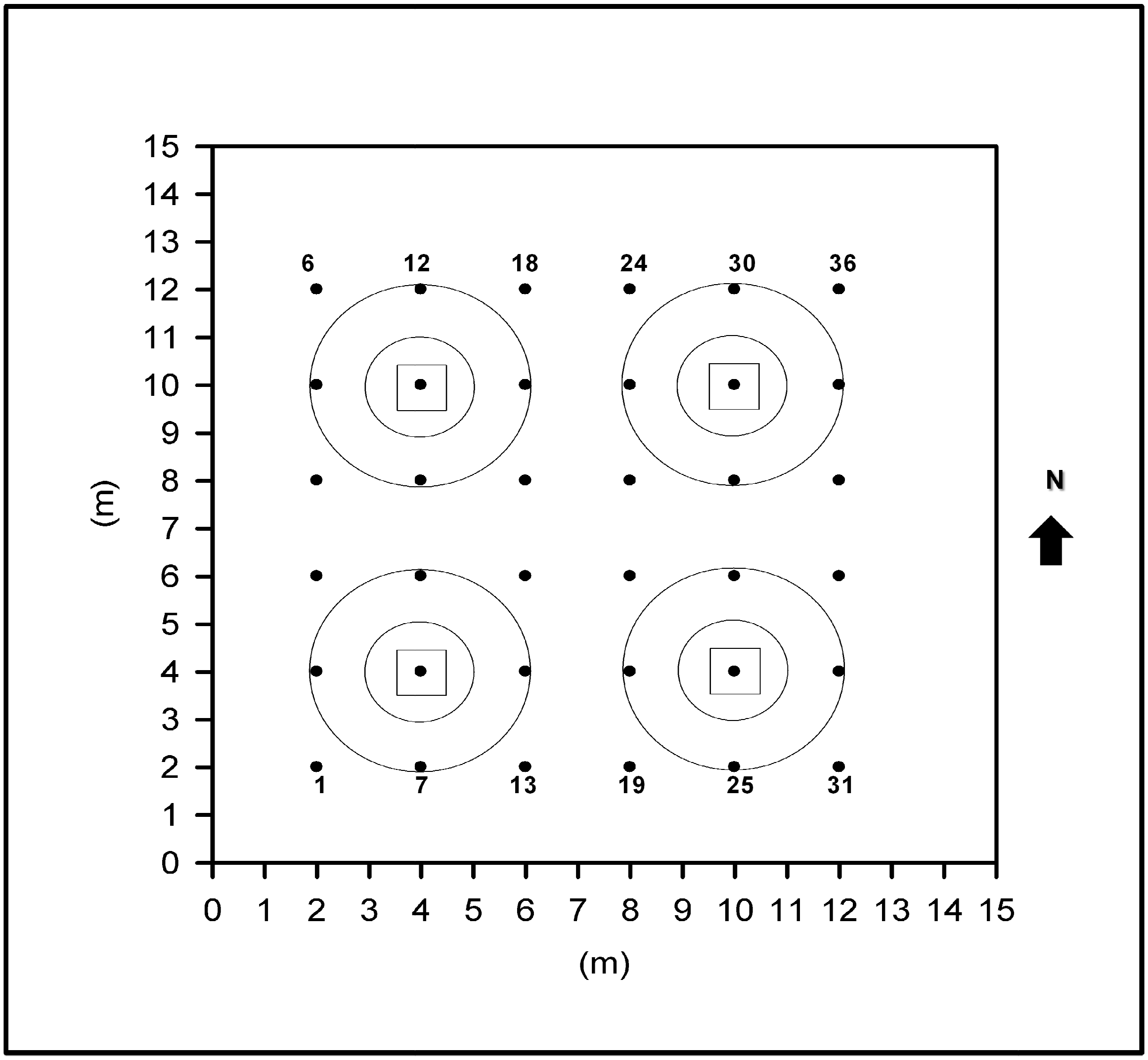

Figure 2. Sampling plots within each 15 m x 15 m subplot (Buckley et al., 1998). Plot centers at planting locations 8, 11, 26, and 29.

Statistical Analysis

The experimental design was developed with the intended use of analysis of variance to evaluate treatment effects. A Randomized Block Design was used and all *F* tests were reported at $\alpha = .05$ significance level. Pair-wise comparisons of fire temperature, canopy composition, and canopy cover treatment means were conducted using Tukey's Honestly Statistical Difference (HSD) at $\alpha = 0.05$. Separate analyses using reduced models were conducted within canopy composition types when overall ANOVA indicated statistical canopy composition by canopy cover interactions. Data were arranged by several categories (species, mean heights, caged vs. uncaged) and analyzed separately, but statistical differences were analyzed and reported across canopy composition and canopy cover treatment. The ANOVA model used to examine effects of canopy composition and canopy cover treatment was:

$$Y_{i(j)k} = \mu + \beta_j + \tau_{i(j)} + \gamma_k + \beta\gamma_{jk} + \gamma\tau_{i(j)k} + \varepsilon_{i(j)k}$$

where:
μ = Overall Mean
β_j = Canopy Composition
$\tau_{i(j)}$ = Block (Canopy Compostion)
γ_k = Canopy Cover Treatment
$\beta\gamma_{jk}$ = Canopy Composition x Canopy Cover Treatment
$\gamma\tau_{i(j)k}$ = Canopy Cover Treatment x Block (Canopy Composition)
$\varepsilon_{i(j)k}$ = Error term consisting of the interaction $\tau\gamma\lambda_{i(j)k}$

i = 1, 2, 3
j = 1, 2
k = 1, 2, 3, 4

Prescribed fires contained only one treatment level and were not included in the ANOVA model. Fire effects were measured by comparing conditions before and after each burn. One-tailed t-tests were used to evaluate paired differences between pre- and post-burn planted oak sprout heights and natural regeneration stem densities associated with each fire. Unexpected paired differences were also tested for significance using one-tailed t-tests. Simple linear regression and multiple linear regression were used to examine relationships between post-burn planted oak sprout height and pre-burn planted oak sprout height, fire temperature, and percent canopy cover.

RESULTS

Fire Temperatures

Mean maximum temperatures of Fire 2 (108°C) were greater than Fire 1 (81°C) across all treatments (P = <0.0001). Mean temperatures in oak stands were lower than in pine stands for both fires (Fig. 3). Within oak stands, mean Fire 2 temperatures were 5°C higher than Fire 1 temperatures, which was not statistically different (P = 0.5894). Within pine stands, mean temperatures of Fire 2 were 51°C higher than Fire 1, which was statistically different (P = <0.0001).

Within oak stands, 25% and 75% canopy treatments had the highest mean temperatures for both fires (Fig. 4). There were no statistical differences between canopy treatments for Fire 1, but clearcut and 25% canopy treatments differed for Fire 2 (Fig. 4). Within pine stands, mean temperatures in clearcut treatments were statistically lower than other canopy treatments for both fires (Fig. 5).

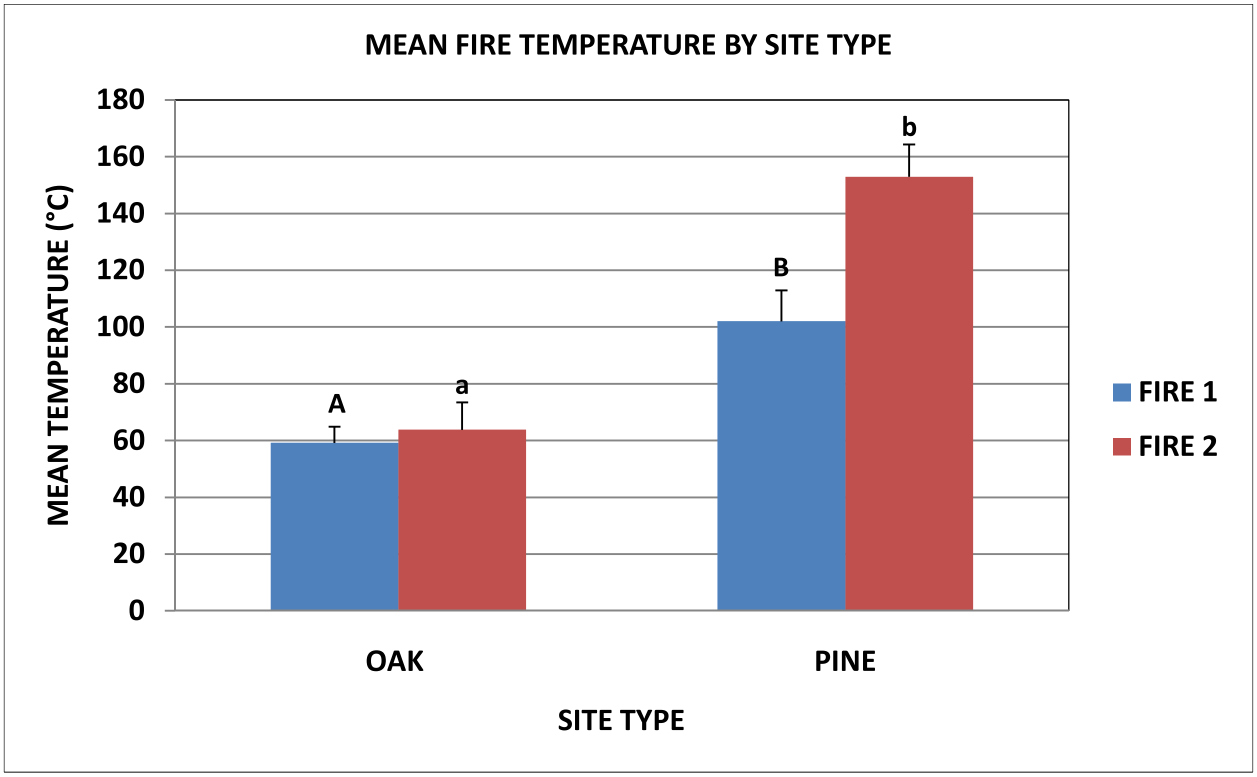

Figure 3. Mean fire temperatures (°C) by fire and site type. Means with the same letter are not statistically different based on Tukey's HSD (α = 0.05). Uppercase letters indicate statistical differences in fire temperatures between site type within Fire 1 (2002). Lowercase letters indicate statistical differences in fire temperatures between site type within Fire 2 (2008). Error bars represent standard error of the mean.

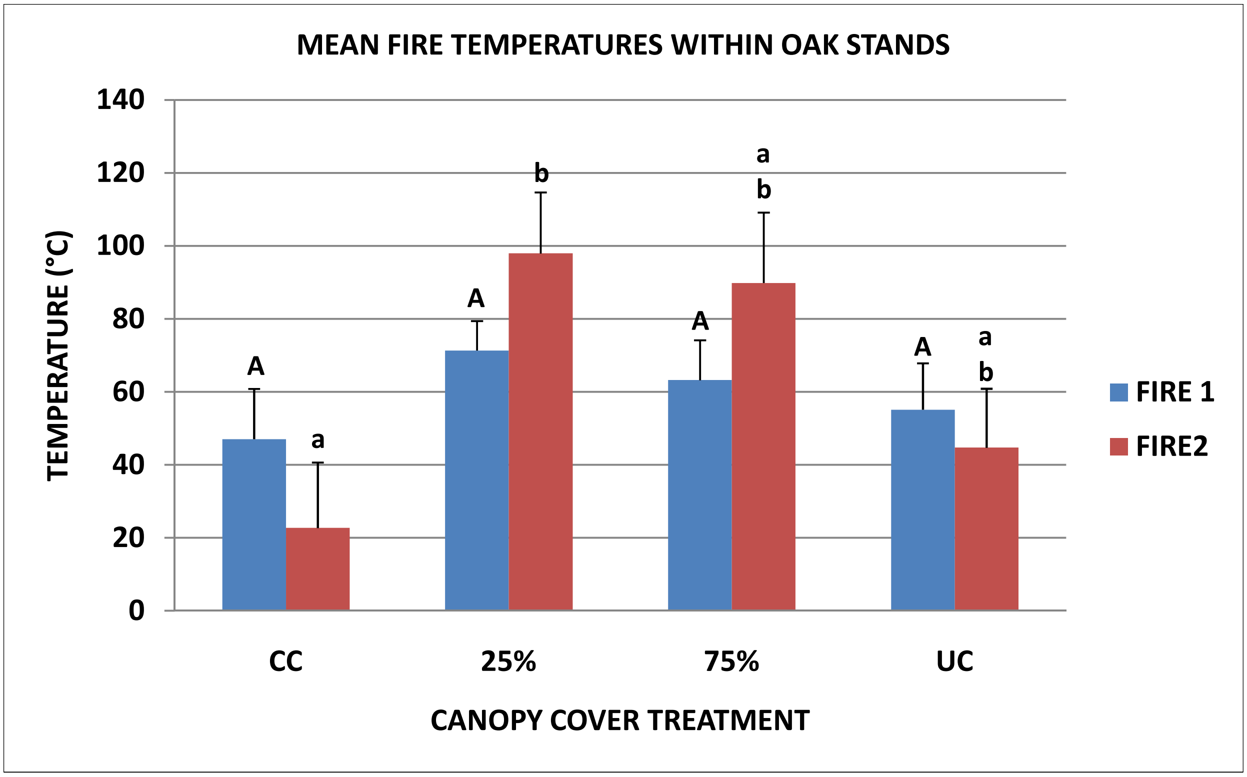

Figure 4. Mean fire temperatures (°C) by fire and canopy cover treatment within oak stands. Means with the same letter are not statistically different between based on Tukey's HSD (α = 0.05). Uppercase letters indicate statistical differences in fire temperatures within Fire 1 (2002). Lowercase letters indicate statistical differences in fire temperatures within Fire 2 (2008). Error bars represent standard error of the mean.

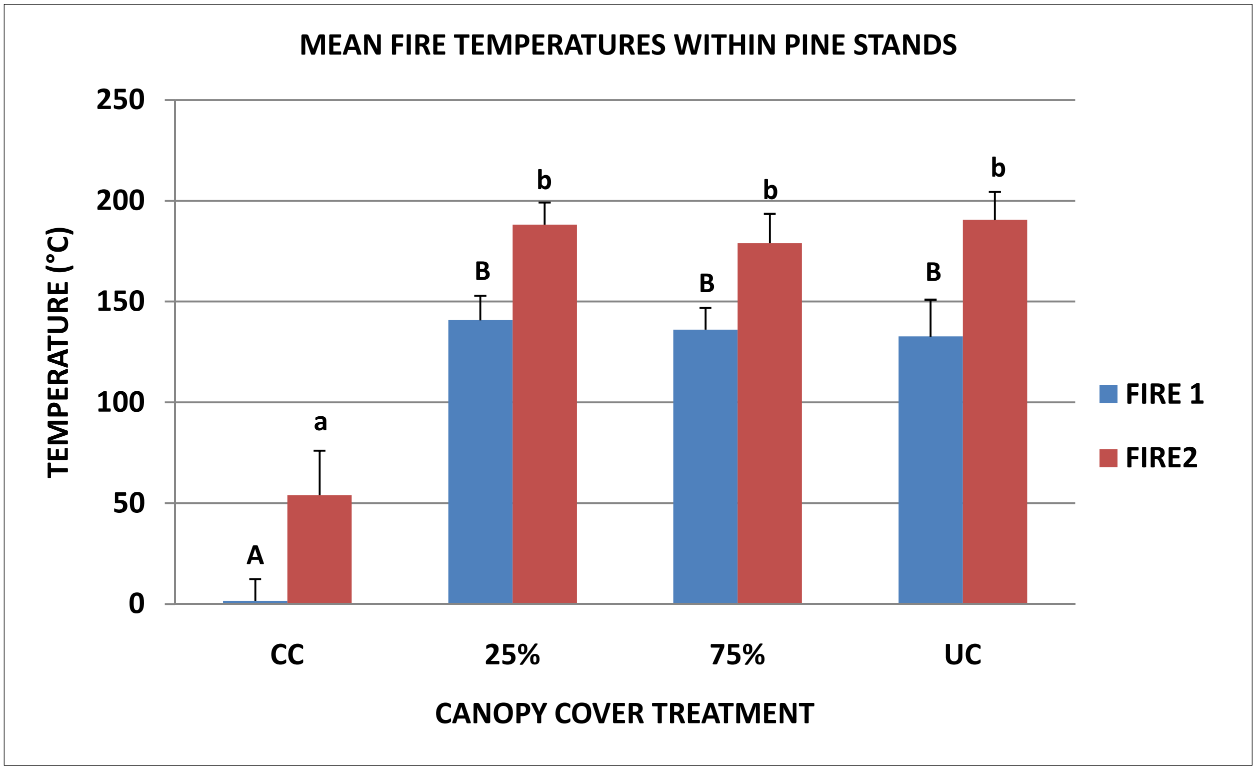

Figure 5. Mean fire temperatures (°C) by fire and and canopy cover treatment within pine stands. Means with the same letter are not statistically different based on Tukey's HSD (α = 0.05). Uppercase letters indicate statistical differences in fire temperatures within Fire 1 (2002). Lowercase letters indicate statistical differences in fire temperatures within Fire 2 (2008). Error bars represent standard error of the mean.

Canopy Cover

By 2009, percent canopy cover in all treatments had increased since implementation of canopy treatments in 1990-1991. Mean percent canopy cover was statistically higher in oak stands than in pine (Fig. 6), likely because oak stands contained a more robust midstory than pine stands.

Within oak stands, 2009 mean canopy cover levels had risen to ~ 70 percent cover in clearcut and 25% canopy treatments (Fig. 7), while canopy cover in the 75% canopy and uncut control treatments approached 90 percent cover (Fig. 7). Clearcut and 25% canopy treatment means were statistically different from uncut canopy means, but did not differ from each other or 75% canopy treatments (Fig. 7).

Within pine stands, mean canopy cover levels in 209 had risen to ~ 10 percent in clearcut treatments, ~ 55 percent in 25% canopy treatments, nearly 80 percent in 75% canopy treatments, and ~ 85 percent in uncut treatments (Fig. 8). Only 75% canopy and uncut treatments means were not statistically different from each other (Fig. 8).

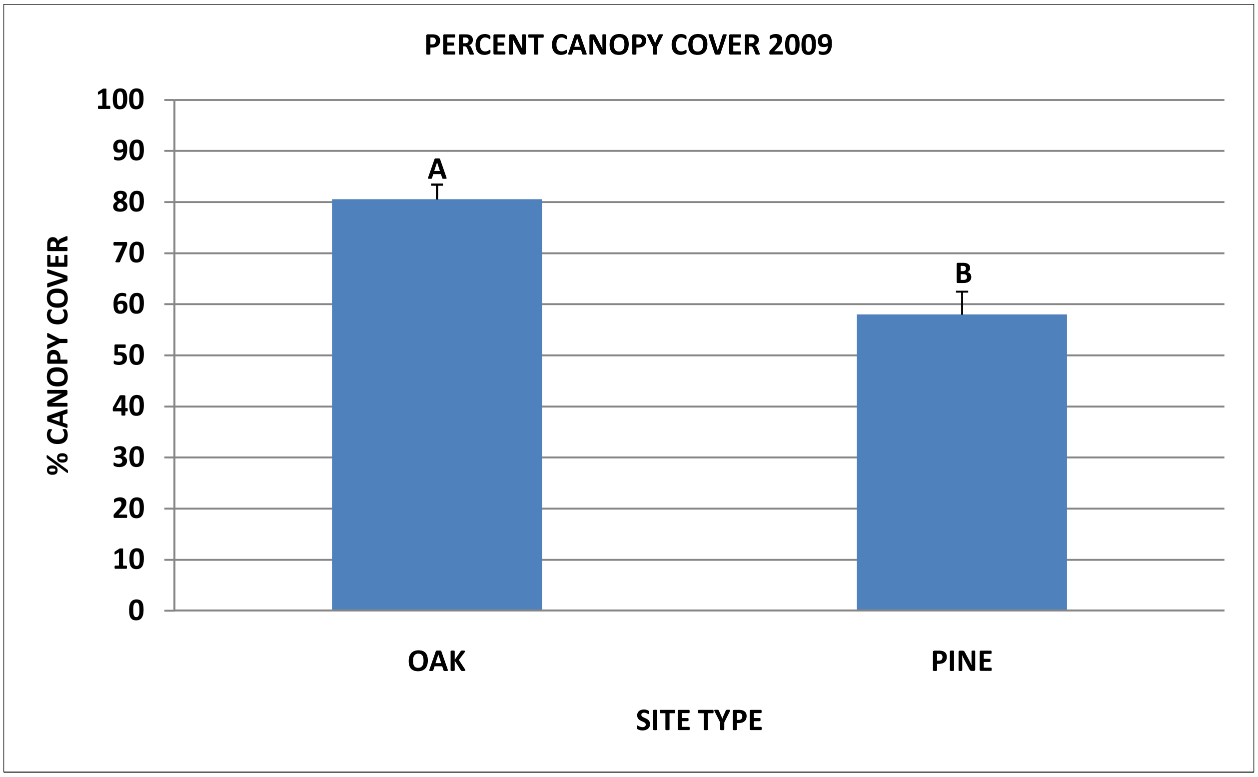

Figure 6. Percent canopy cover by site type 2009. Means with the same letter are not statistically different based on Tukey's HSD (α = 0.05). Error bars represent standard error of the mean.

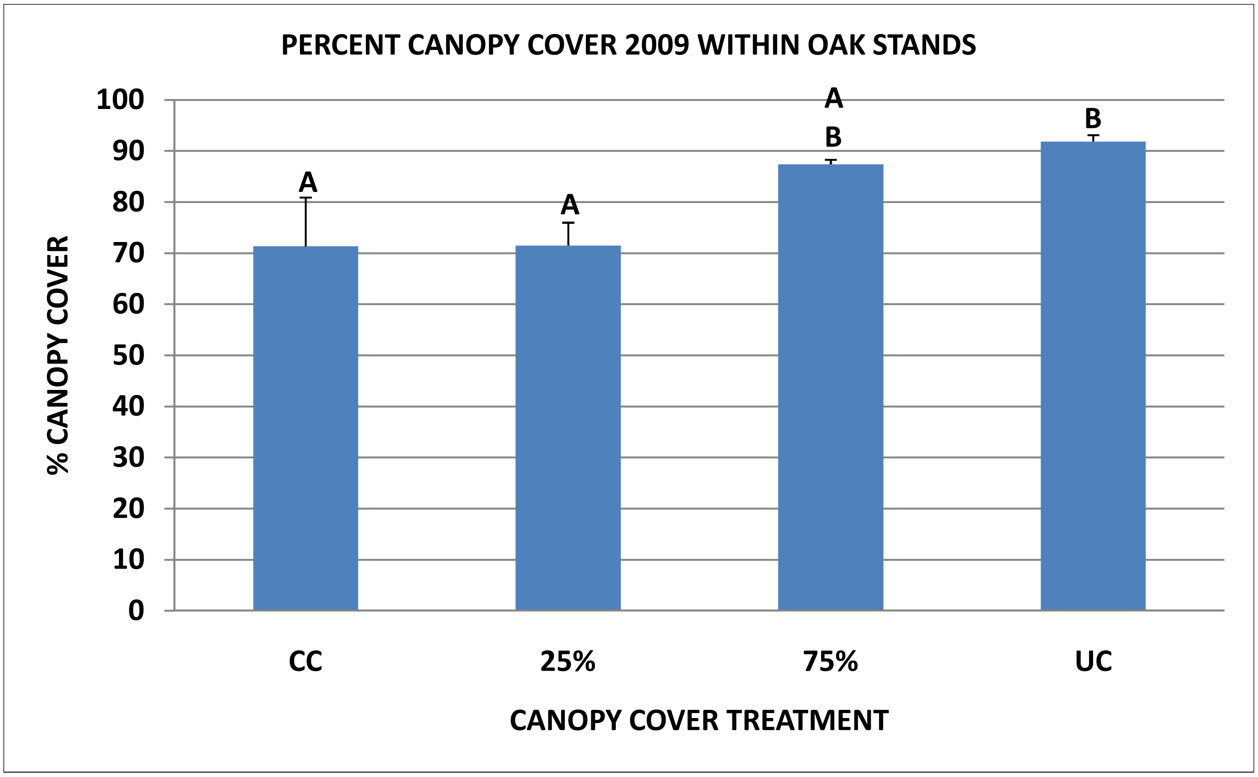

Figure 7. Percent canopy cover by canopy treatment within oak stands 2009. Canopy treatment codes are as described in Fig. 1. Means with the same letter are not statistically different based on Tukey's HSD (α = 0.05). Error bars represent standard error of the mean.

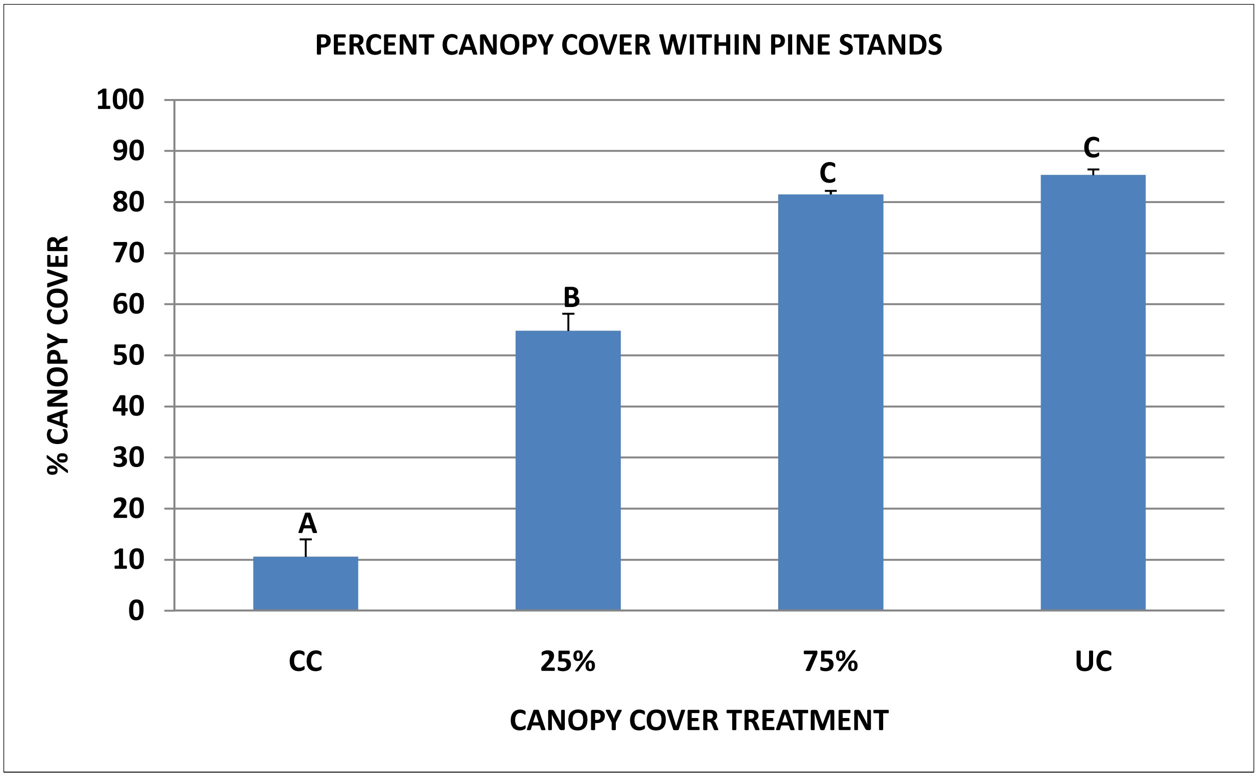

Figure 8. Percent canopy cover by canopy treatment within pine stands 2009. Canopy treatment codes are as described in Fig. 1. Means with the same letter are not statistically different based on Tukey's HSD (α = 0.05). Error bars represent standard error of the mean.

Objective 1: Planted Northern Red Oak Sprout Heights

Mean heights of caged oak stems planted within oak stands were greatest in clearcut treatments in all sampling years, followed by 25% cover, 75% cover, and control treatments respectively (Fig. 9). Differences among canopy treatments became less distinct in 2003 and 2009, following each fire (Fig. 9). In contrast, mean heights of caged oak stems planted within pine stands were greatest in 25% canopy treatments in all years but 2009, when mean height was greatest in clearcut treatments (Fig. 10). Differences among canopy treatments were not statistically different in any sampling year at the $\alpha = 0.05$ significance level (Fig. 10).

Mean heights of uncaged oak stems planted within oak stands were greatest in 25% canopy treatments, followed by clearcut, 75%, and control treatments beginning in 2003, following Fire 1 (Fig. 11). This pattern held through 2009. Clearcut and 25% canopy treatment heights did not differ in any sampling year. Clearcut and 25% canopy treatments differed from 75% and control treatments in all years but 2009, when the only difference in mean height of caged oak seedlings was found in the 25% and control treatments (Fig. 11). Mean heights of uncaged oak stems planted within pine stands were much smaller than caged stems within pine stands. Differences in mean heights were not statistically significant following Fire 1 (Fig. 12). No survivors occurred in some sampling plots in clearcut treatments following Fire 1 (Fig. 12).

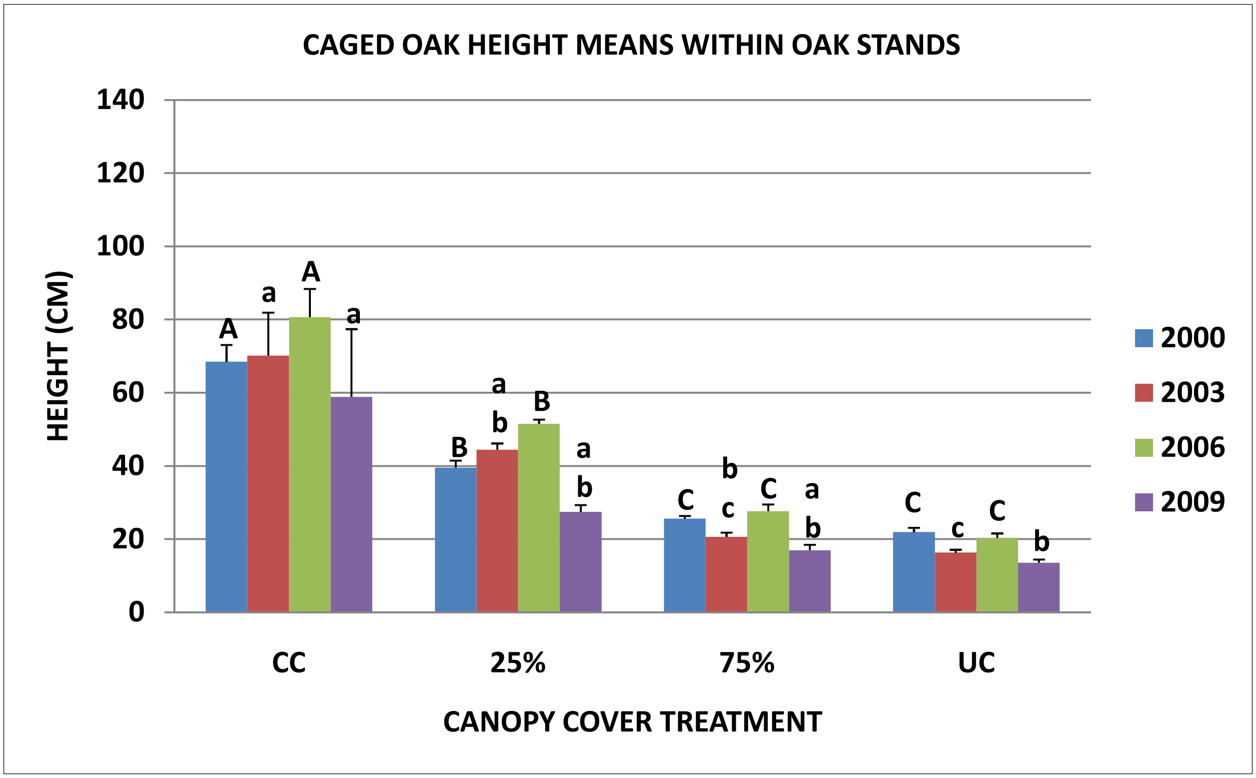

Figure 9. Caged planted oak mean heights within oak stands by year. Canopy cover treatment codes are as described in Fig. 1. Within years, means with the same letter are not statistically different among canopy cover treatments based on Tukey's HSD (α = 0.05). Letters correspond to differences among canopy cover treatments within each year. Error bars represent standard error of the mean.

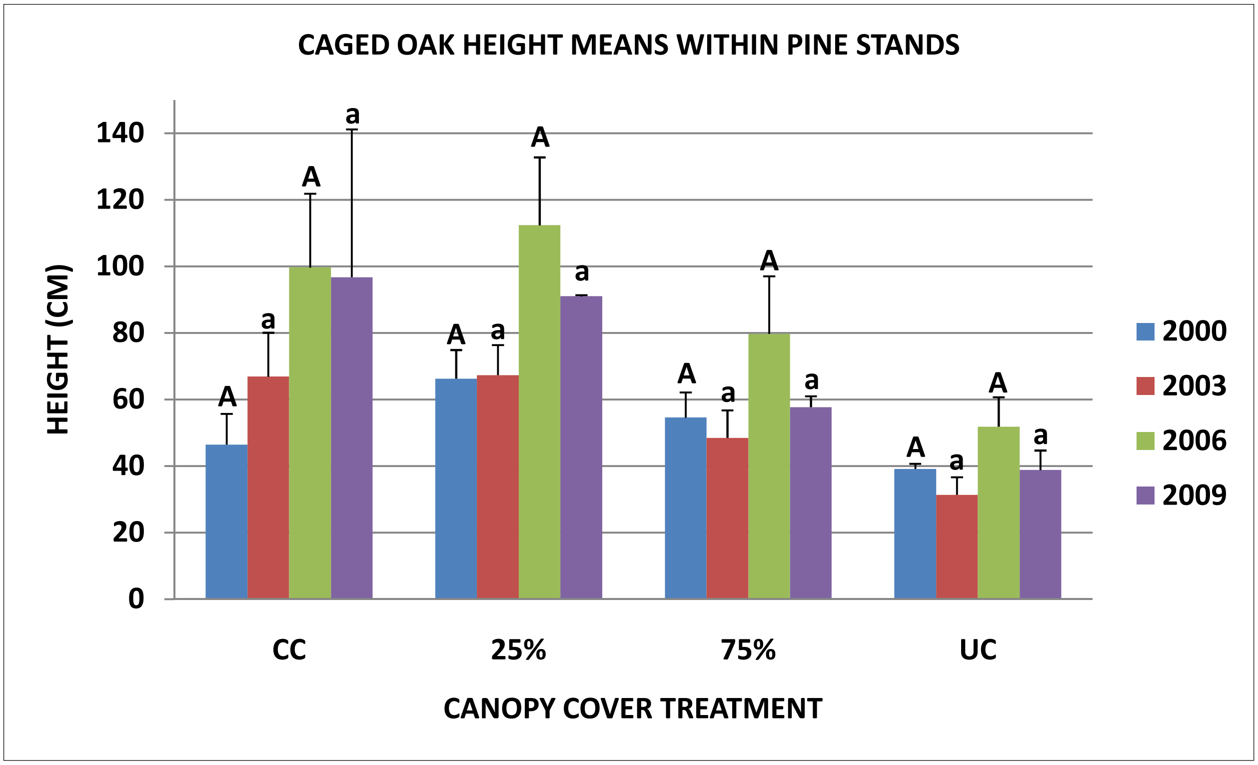

Figure 10. Caged planted oak mean heights within pine stands by year. Canopy cover treatment codes are as described in Fig. 1. Within years, means with the same letter are not statistically different among canopy treatments based on Tukey's HSD (α = 0.05). Letters correspond to differences among canopy cover treatments within each year. Error bars represent standard error of the mean.

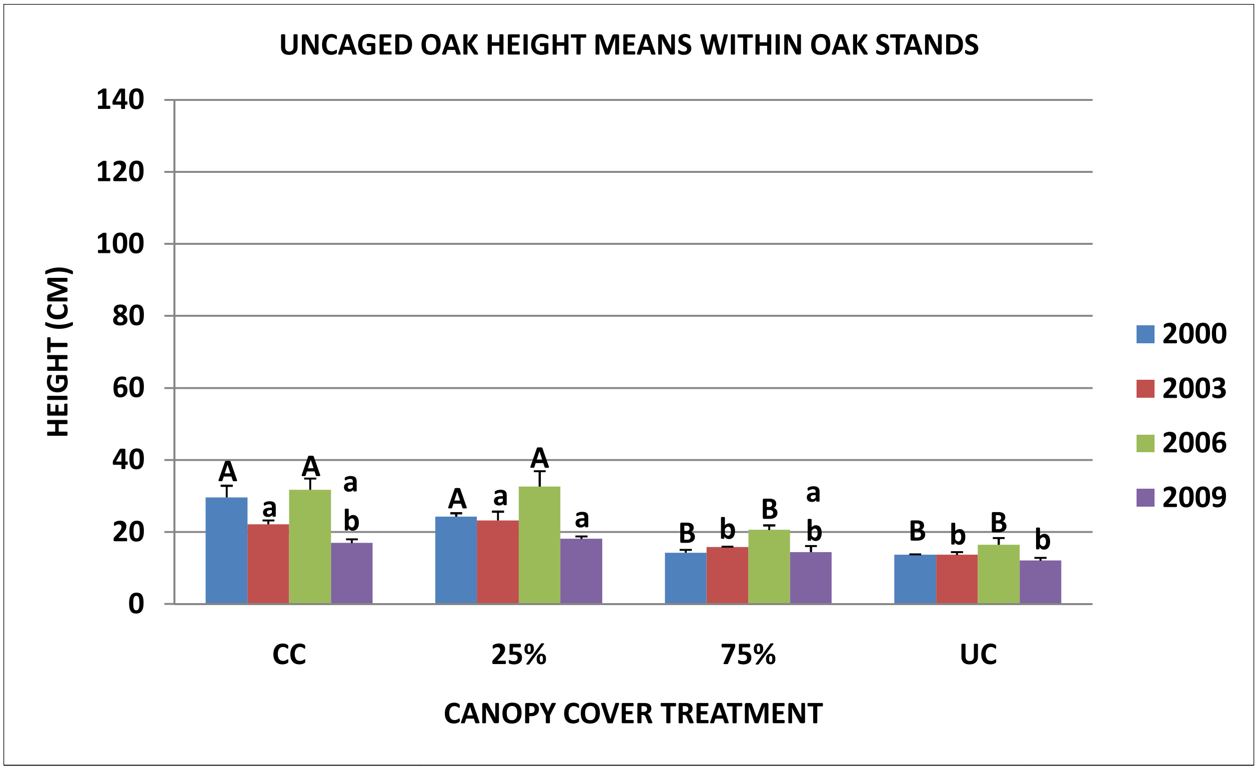

Figure 11. Uncaged planted oak mean heights within oak stands by year. Canopy cover treatment codes are as described in Fig. 1. Within years, means with the same letter are not statistically different among treatments based on Tukey's HSD (α = 0.05). Letters correspond to differences among canopy cover treatments within each year. Error bars represent standard error of the mean.

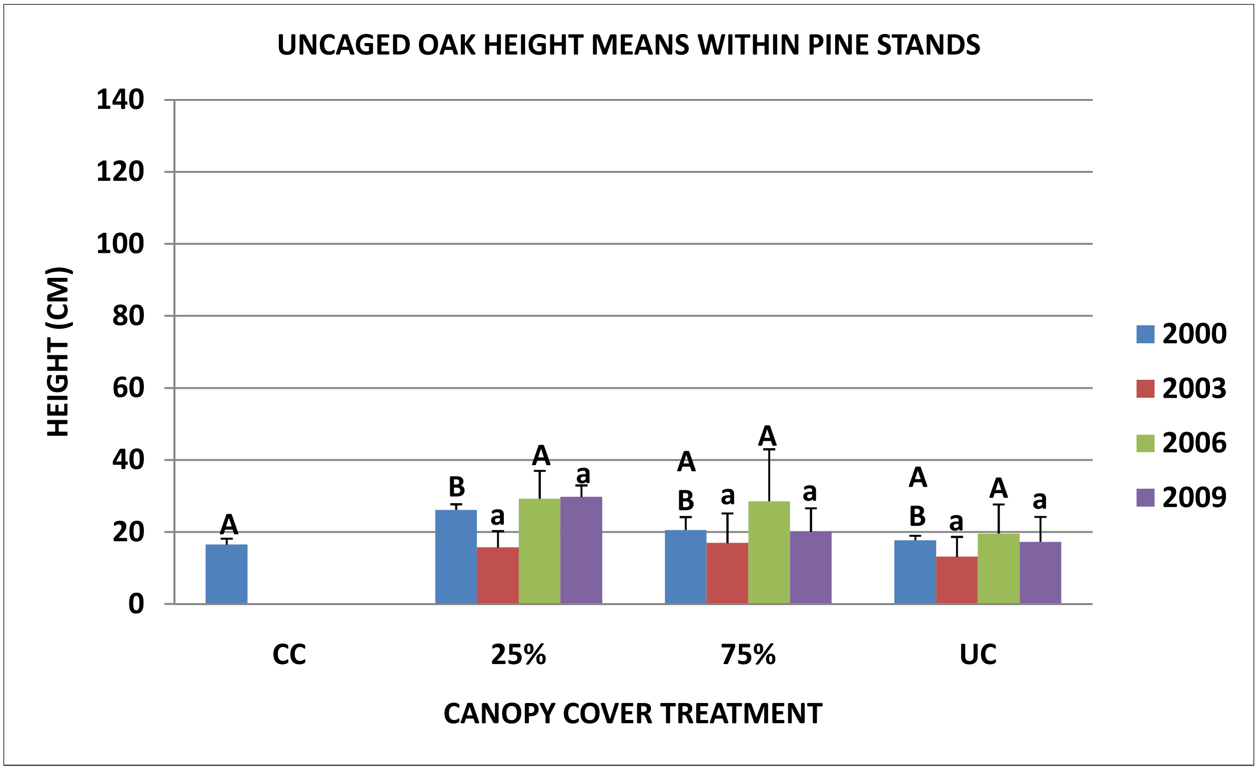

Figure 12. Uncaged planted oak mean heights within pine stands by year. Canopy cover treatment codes are as described in Fig. 1. Within years, means with the same letter are not statistically different among treatments based on Tukey's HSD (α = 0.05). Letters correspond to differences among canopy cover treatments within each year. No uncaged planted oaks survived in pine clearcuts beyond 2000. Error bars represent standard error of the mean.

Mean heights of caged seedlings planted within oak stands were lower following Fire 2 than following Fire 1 in all canopy treatments (Fig. 13). Differences in mean height were statistically different in all treatments (Table 1). Differences were greatest in clearcut and 25% canopy treatments, where pre-burn heights had been greatest (Fig. 13). Mean heights of caged seedlings planted within pine stands were greater following Fire 2 than following Fire 1 in all canopy treatments (Fig. 14). Mean height differences were statistically different in all but clearcut treatments ($P = 0.3726$) (Table 1).

Mean heights of uncaged seedlings planted within oak stands were smaller following Fire 2 than following Fire 1 in all canopy treatments (Fig. 15). Mean height differences were statistically different in all canopy treatments (Table 1).

Mean heights of uncaged seedlings planted within pine stands were greater following Fire 2 than following Fire 1 in all canopy treatments (Fig. 16). Differences in mean height were statistically different in 25% canopy ($P = 0.0017$) and uncut control ($P = 0.0028$) treatments, where the mean differences were 10.02 cm and 5.42 cm respectively (Table 1).

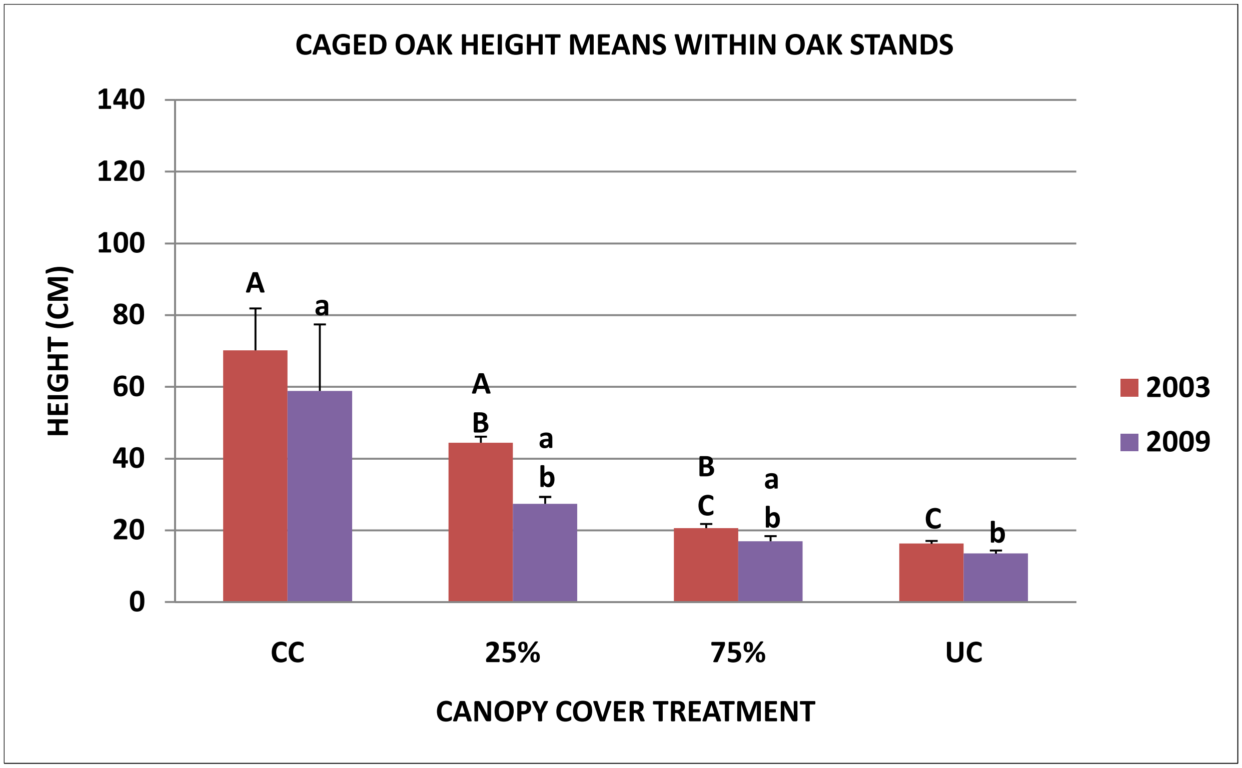

Figure 13. Caged planted oak mean heights within oak stands in 2003 and 2009, two growing seasons after each fire. Canopy cover treatment codes are as described in Fig. 1. Means with the same letter are not statistically different based on Tukey's HSD (α = 0.05). Uppercase letters correspond to differences among canopy cover treatments two growing seasons after Fire 1. Lowercase letters correspond to differences among canopy cover treatments two growing seasons after Fire 2. Error bars represent standard error of the mean.

Table 1. Mean height differences for planted oak two growing seasons after each prescribed fire by cage, site type, and canopy cover. Bold P- values indicate statistical height differences based on results of one-tailed t-tests at $\alpha = 0.05$ significance. N indicates number of trees present in both 2003 and 2009.

CAGING	COVER TYPE	CANOPY TREATMENT	MEAN HT DIFFERENCE (CM) 2009 - 2003	SE	P-VALUE	N
CAGED	**OAK**	**CC**	-17.75	8.66	0.049	32
		25%	-19.33	2.33	**<0.0001**	72
		75%	-5.93	1.17	**<0.0001**	58
		UC	-5.65	1.17	**<0.0001**	40
CAGED	**PINE**	**CC**	10.37	11.44	0.3726	30
		25%	22.65	3.34	**<0.0001**	109
		75%	9.57	1.84	**<0.0001**	124
		UC	8.08	1.64	**<0.0001**	115
UNCAGED	**OAK**	**CC**	-4.57	1.48	**0.0038**	37
		25%	-5.44	1.35	**0.0001**	87
		75%	-3.14	1.13	**0.0072**	66
		UC	-2.31	0.76	**0.0039**	52
UNCAGED	**PINE**	**CC**	0.82	2.9	0.7804	17
		25%	10.02	3.03	**0.0017**	54
		75%	0.97	1.45	0.5028	83
		UC	5.42	1.73	**0.0028**	55

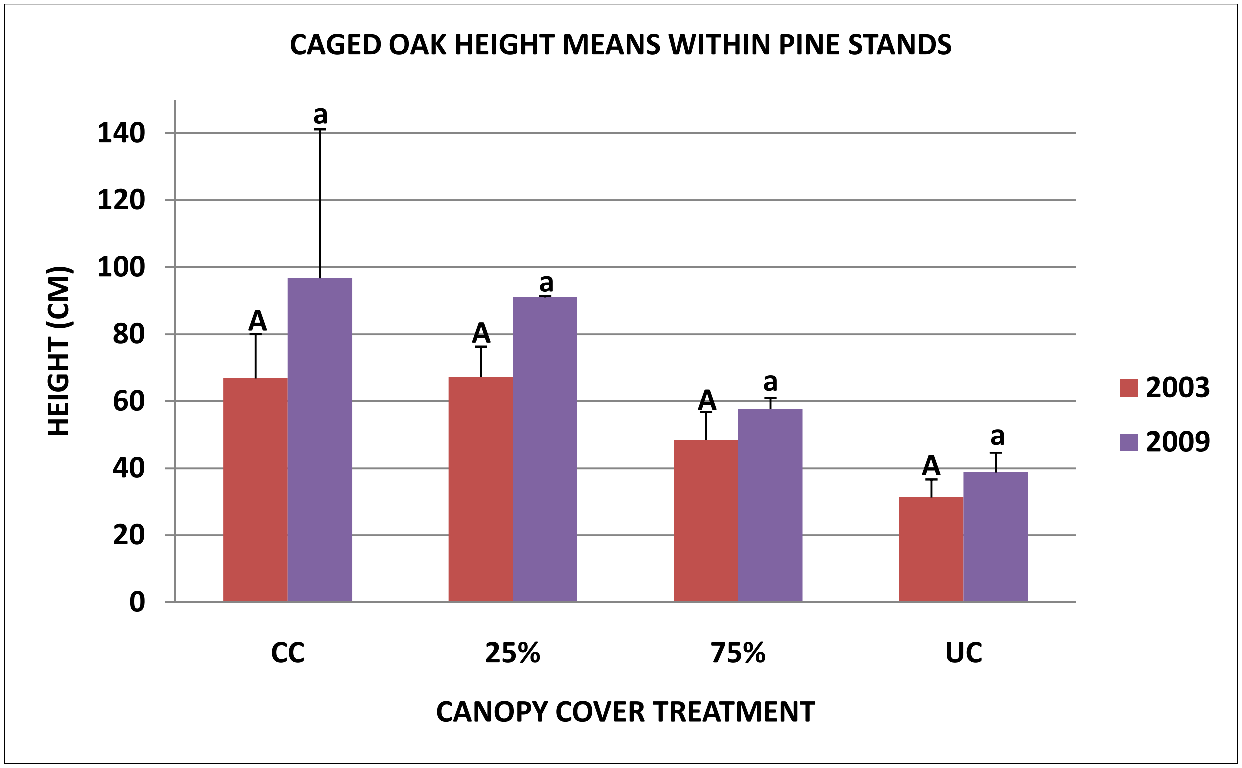

Figure 14. Caged planted oak mean heights within pine stands in 2003 and 2009, two growing seasons after each fire. Canopy cover treatment codes are as described in Fig. 1. Means with the same letter are not statistically different based on Tukey's HSD (α = 0.05). Uppercase letters correspond to differences among canopy cover treatments two growing seasons after Fire 1. Lowercase letters correspond to differences among canopy cover treatments two growing seasons after Fire 2. Error bars represent standard error of the mean.

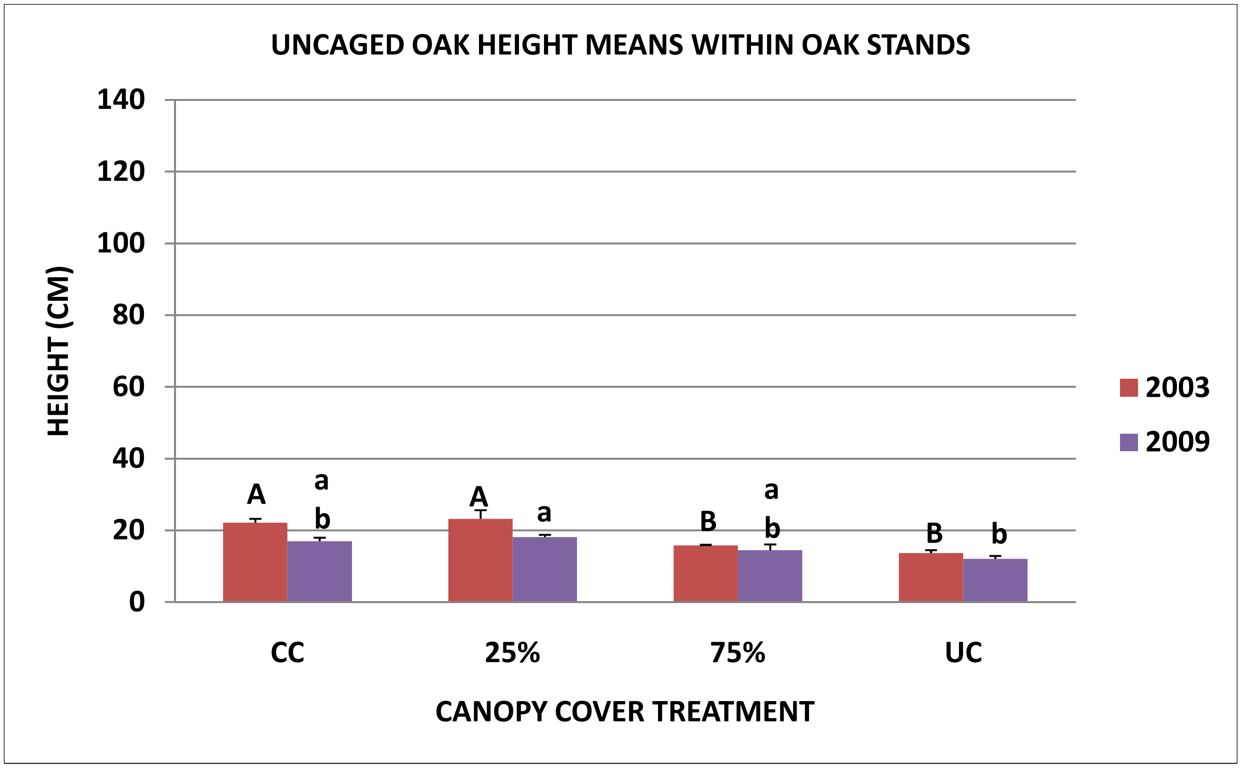

Figure 15. Uncaged planted oak mean heights within oak stands in 2003 and 2009, two growing seasons after each fire. Canopy cover treatment codes are as described in Fig. 1. Means with the same letter are not statistically different based on Tukey's HSD (α = 0.05). Uppercase letters correspond to differences among canopy cover treatments two growing seasons after Fire 1. Lowercase letters correspond to differences among canopy cover treatments two growing seasons after Fire 2. Error bars represent standard error of the mean.

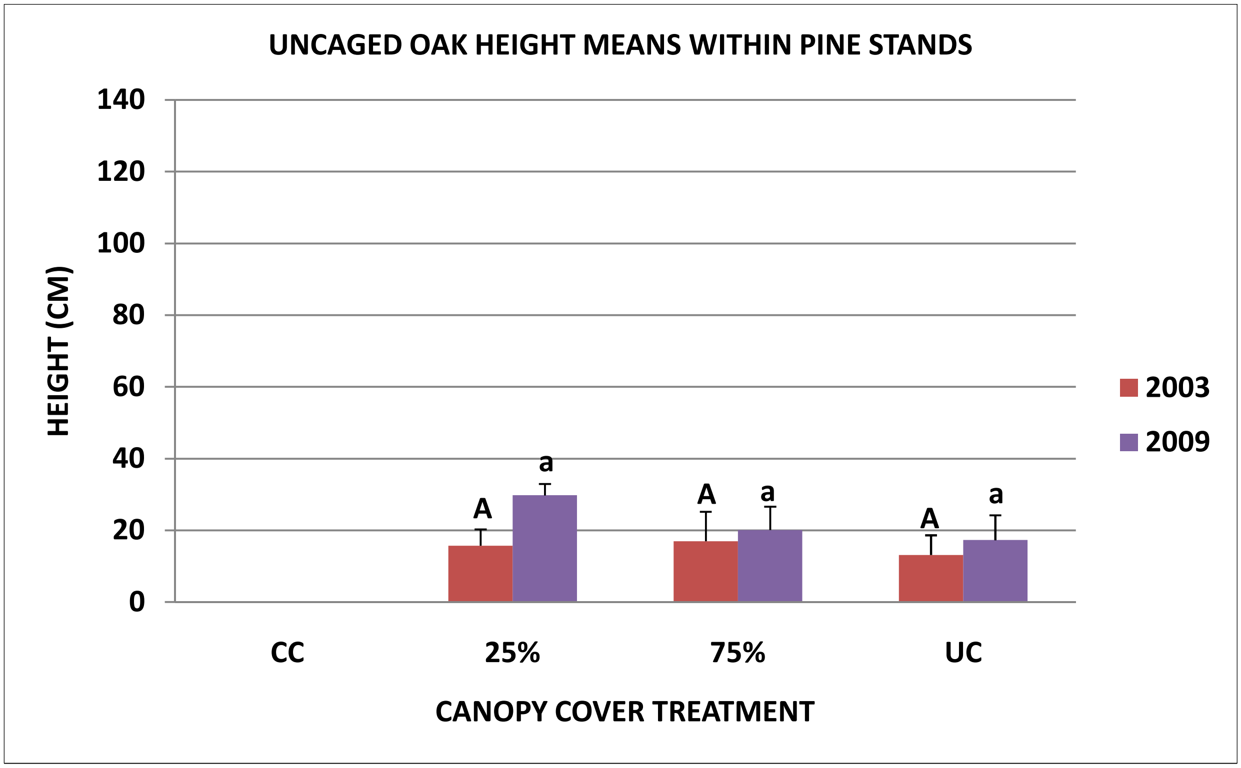

Figure 16. Uncaged planted oak mean heights within pine stands in 2003 and 2009, two growing seasons after each fire. Canopy cover treatment codes are as described in Fig. 1. Means with the same letter are not statistically different based on Tukey's HSD (α = 0.05). Uppercase letters correspond to differences among canopy cover treatments two growing seasons after Fire 1. Lowercase letters correspond to differences among canopy cover treatments two growing seasons after Fire 2. Error bars represent standard error of the mean.

Objective 2: Response of Red Maple to Prescribed Fire

Density of red maple in all size classes was greater within oak stands than pine stands (Fig. 17-18). Density of small red maple in oak stands increased substantially after Fire 2 in clearcut and 25% cover treatments, decreased substantially after Fire 1 in 75% cover treatments, and rebounded to pre-burn densities in the uncut controls (Fig. 17). Small red maple densities within oak stands increased in 25% cover treatments, but decreased in clearcut, 75% cover, and uncut control treatments following Fire 1 (Fig. 17). Reductions in red maple density were statistically significant in 75% cover (P = 0.0068) and uncut control treatments (P = <0.0001) following Fire 1 (Table 2). Small red maple densities in oak stands increased in all canopy treatments following Fire 2 (Fig. 17). Increases in Small red maple stems per hectare were statistically different in clearcut (P = 0.0012) and 25% cover (P = 0.0033) treatments (Table 3).

Overall, Small red maple densities were lower overall in pine stands than in oak stands (Fig. 17-18). Within pine stands, Small red maple densities were statistically higher in uncut control treatments than other canopy cover treatments in all years except 2003 (Fig. 18). Mean densities were not statistically different among other canopy cover treatments in any sampling year. Small red maple stems per hectare decreased in all treatments following both fires (Fig. 18). Decreases in red maple density were statistically significant in 75% cover (P = 0.0408) and uncut control (P = <0.0001) treatments following Fire 1, but only significant in the uncut control treatments (P = 0.0064) following Fire 2 (Tables 2-3).

Within oak stands, Medium red maple densities in 25% cover and 75% cover treatments were statistically higher than densities in clearcut and uncut treatments in all years except 2001, when uncut control treatment means were not statistically lower (Fig. 19). Medium red maple density in 25% cover and 75% cover treatments did not differ in any sampling year (Fig. 19).

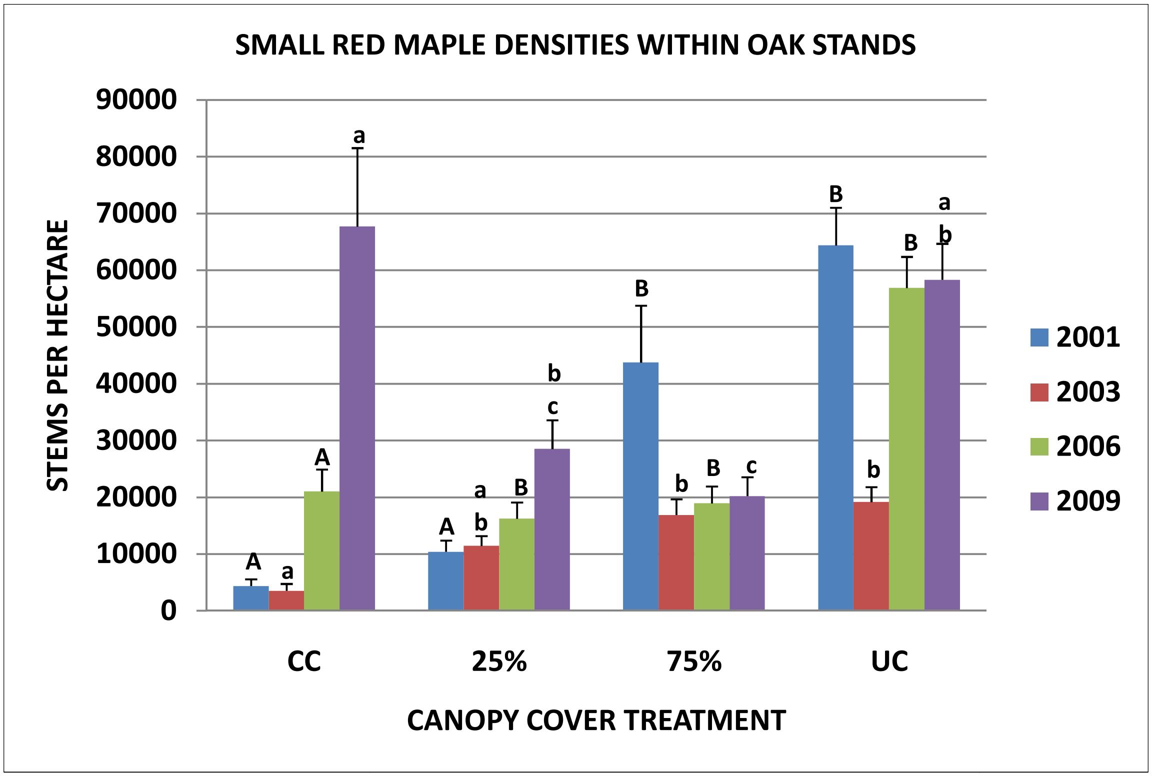

Figure 17. Small red maple genet densities within oak stands by year. Canopy cover treatment codes are as described in Fig. 1. Within years, means with the same letter are not statistically different among treatments based on Tukey's HSD (α = 0.05). Letters correspond to differences among canopy cover treatments within each year. Error bars represent standard error of the mean.

Table 2. Red maple natural regeneration stems per hectare by size class, site type, and canopy cover treatment. Bold P-values indicate statistical differences between pre-burn and post-burn densities following Fire 1 based on one-tailed t-tests at α= 0.05 significance. N = 48 sample plots per canopy treatment.

SIZE CLASS	SITE	CANOPY TREATMENT	STEMS PER HECTARE 2001	2003	DIFFERENCE FIRE 1	P-VALUE	PERCENT DIFFERENCE FIRE 1
SMALL	**OAK**	**CC**	4375	3541.67	-833.33	0.3994	**-19.04%**
		25%	10416.67	11458.33	1041.66	0.6885	**10.00%**
		75%	43750	16875	-26875	**0.0068**	**-61.42%**
		UC	64375	19166.67	-45208.33	**<0.0001**	**-70.27%**
	PINE	**CC**	208.33	0	-208.33	0.3224	**-100.00%**
		25%	1250	1041.67	-208.33	0.7427	**-16.67%**
		75%	4166.67	833.33	-3333.33	**0.0408**	**-80.00%**
		UC	10000	208.33	-9791.67	**<0.0001**	**-97.92%**
MEDIUM	**OAK**	**CC**	9416.68	4244.14	-5172.54	**<0.0001**	**-54.93%**
		25%	23475.37	13262.92	-10212.45	**<0.0001**	**-43.50%**
		75%	22480.65	12599.78	-9880.88	**<0.0001**	**-43.95%**
		UC	16114.45	6432.52	-9681.93	**<0.0001**	**-60.08%**
	PINE	**CC**	66.31	0	-66.31	0.3224	**-100.00%**
		25%	5902	0	-5835.68	**0.0061**	**-98.88%**
		75%	795.78	0	-795.78	0.0766	**-100.00%**
		UC	331.57	0	-331.57	0.0959	**-100.00%**
LARGE	**OAK**	**CC**	2287.85	1177.08	-1110.77	**0.0055**	**-48.55%**
		25%	1823.65	629.99	-1193.66	**0.0016**	**-65.45%**
		75%	646.57	132.63	-513.94	**0.0004**	**-79.49%**
		UC	116.05	16.58	-99.47	0.0832	**-85.71%**
	PINE	**CC**	0	0	0	.	**.**
		25%	66.31	0	-66.31	0.2093	**-100.00%**
		75%	0	0	0	.	**.**
		UC	0	0	0	.	**.**

Table 3. Red maple natural regeneration stems per hectare by size class, site type, and canopy cover treatment. Bold P-values indicate statistical differences between pre-burn and post-burn densities following Fire 2 based on one-tailed t-tests at α= 0.05 significance. N = 48 sample plots per canopy treatment.

SIZE CLASS	SITE	CANOPY TREATMENT	STEMS PER HECTARE 2006	2009	DIFFERENCE FIRE 2	P-VALUE	PERCENT DIFFERENCE FIRE 2
SMALL	**OAK**	**CC**	21041.67	67708.33	46666.66	**0.0012**	**221.78%**
		25%	16250	28541.67	12291.67	**0.0033**	**75.64%**
		75%	18958.33	20208.33	1250	0.6381	**6.59%**
		UC	56875	58333.33	1458.33	0.8352	**2.56%**
	PINE	**CC**	208.33	0	-208.33	0.3224	**-100.00%**
		25%	1458.33	625	-833.33	0.2093	**-57.14%**
		75%	2291.67	1666.67	-625	0.5692	**-27.27%**
		UC	15208.33	4583.33	-10625	**0.0064**	**-69.86%**
MEDIUM	**OAK**	**CC**	4111.51	2453.64	-1657.87	**0.0286**	**-40.32%**
		25%	14920.79	10941.91	-3978.88	**0.0026**	**-26.67%**
		75%	17772.32	12135.57	-5636.74	**0.0003**	**-31.72%**
		UC	8289.33	4708.34	-3580.99	**<0.0001**	**-43.20%**
	PINE	**CC**	0	0	0	.	**.**
		25%	994.72	331.57	-663.14	**0.0487**	**-66.67%**
		75%	132.63	66.31	-66.31	0.5692	**-50.00%**
		UC	0	0	0	.	**.**
LARGE	**OAK**	**CC**	1110.77	1077.61	-33.16	0.88	**-2.99%**
		25%	613.41	464.2	-149.21	0.29	**-24.32%**
		75%	198.94	82.89	-116.05	**0.0333**	**-58.33%**
		UC	66.31	16.58	-49.74	0.0832	**-75.00%**
	PINE	**CC**	0	0	0	.	**.**
		25%	0	0	0	.	**.**
		75%	0	0	0	.	**.**
		UC	0	0	0	.	**.**

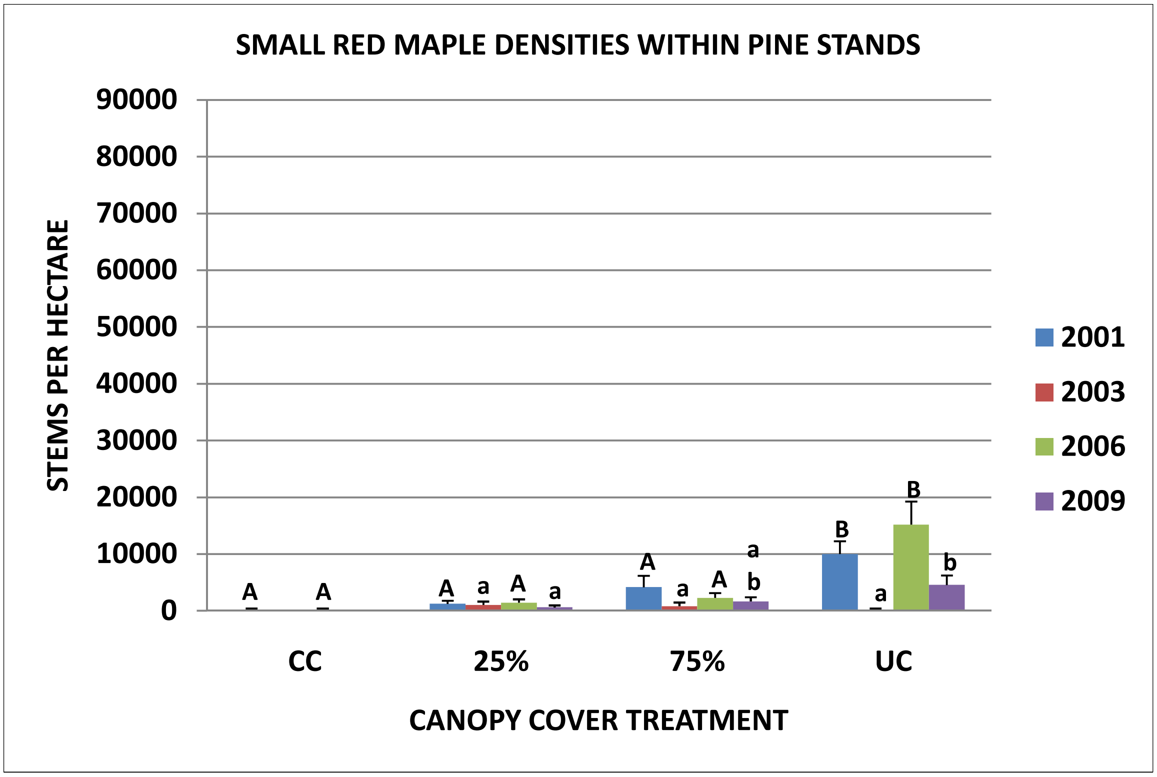

Figure 18. Small red maple genet densities within pine stands by year. Canopy cover treatment codes are as described in Fig. 1. Within years, means with the same letter are not statistically different among treatments based on Tukey's HSD (α = 0.05). Letters correspond to differences among canopy cover treatments within each year. Error bars represent standard error of the mean.

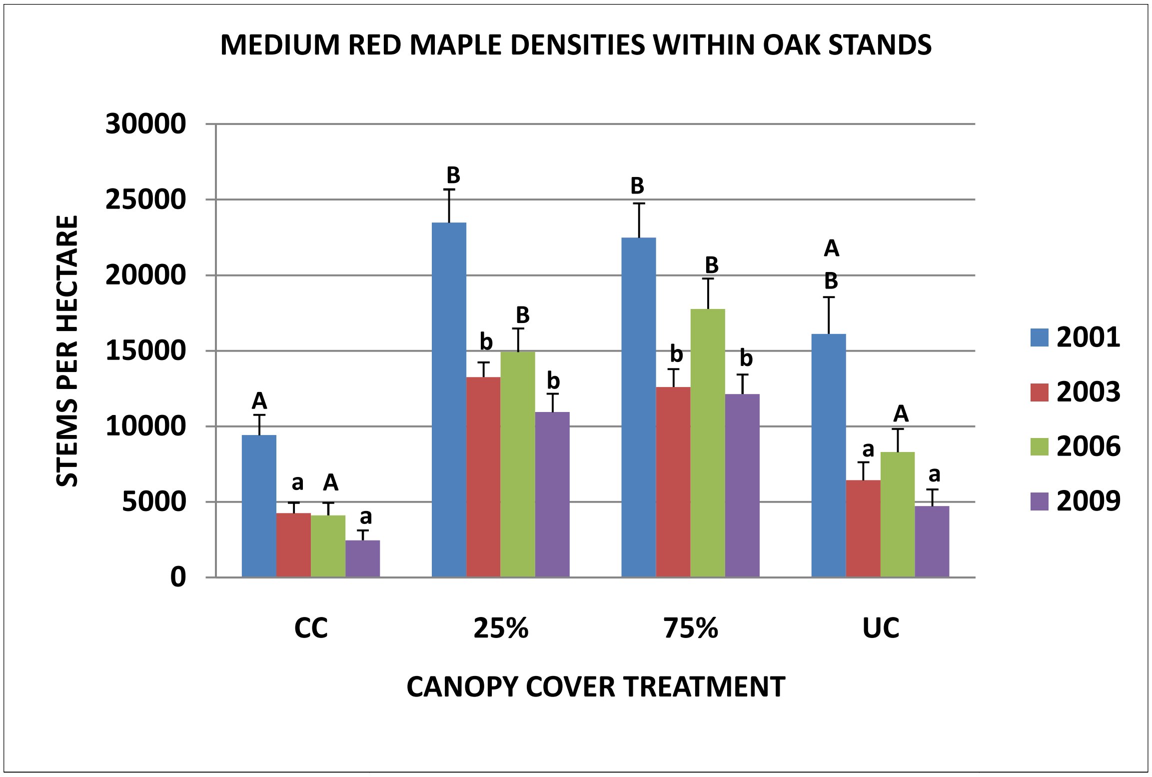

Figure 19. Medium red maple genet densities within oak stands by year. Canopy cover treatment codes are as described in Fig. 1. Within years, means with the same letter are not statistically different among treatments based on Tukey's HSD (α = 0.05). Letters correspond to differences among canopy cover treatments within each year. Error bars represent standard error of the mean.

Stem densities in clearcut and uncut treatments did not differ in any sampling year (Fig. 19). Medium red maple densities within oak stands decreased significantly in all canopy cover treatments following both fires, but were reduced by a greater number following Fire 1 (Fig. 19) (Tables 2-3).

Medium red maple densities in pine stands were lower than in oak stands (Fig. 19-20), and within pine stands, Medium red maple densities did not differ statistically in any canopy treatment after the first sampling year (Fig. 20). Clearcut and uncut control treatments in pine stands contained no Medium red maple stems after 2001 (Fig. 20).

Within oak stands, Large red maple stem densities were highest in clearcut treatments and decreased with increasing canopy cover in all years (Fig. 21). Mean density of Large red maple in clearcut treatments differed statistically from 75% cover and uncut control treatments in all years, and differed from 25% cover treatments in 2009 (Fig. 21). A 2 to 4 fold reduction in the density of Large red maple stems within the oak stands occurred after Fire 1, whereas changes following Fire 2 were minor (Fig. 21). Decreases in density following Fire 1 were statistically significant in all but uncut control treatments ($P = 0.0832$), whereas decreases in stems per hectare following Fire 2 were only statistically significant in 75% cover treatments ($P = 0.0333$) (Tables 2-3). Within pine stands, Large red maple stems were found only in 25% cover treatments in 2001. No Large red maple stems were sampled within pine stands after 2001.

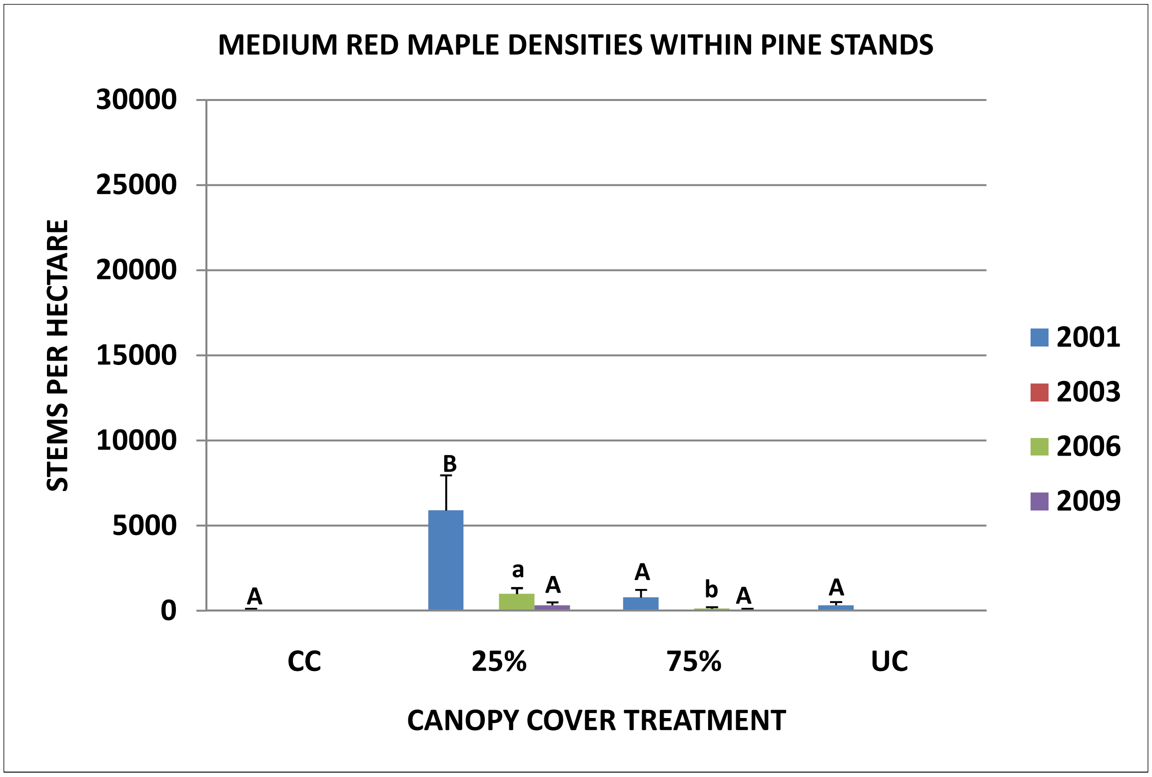

Figure 20. Medium red maple genet densities within pine stands by year. Canopy cover treatment codes are as described in Fig. 1. Within years, means with the same letter are not statistically different among treatments based on Tukey's HSD (α = 0.05). Letters correspond to differences among canopy cover treatments within each year. No Medium red maple stems survived in pine clearcuts or uncut control treatments beyond 2001. Error bars represent standard error of the mean.

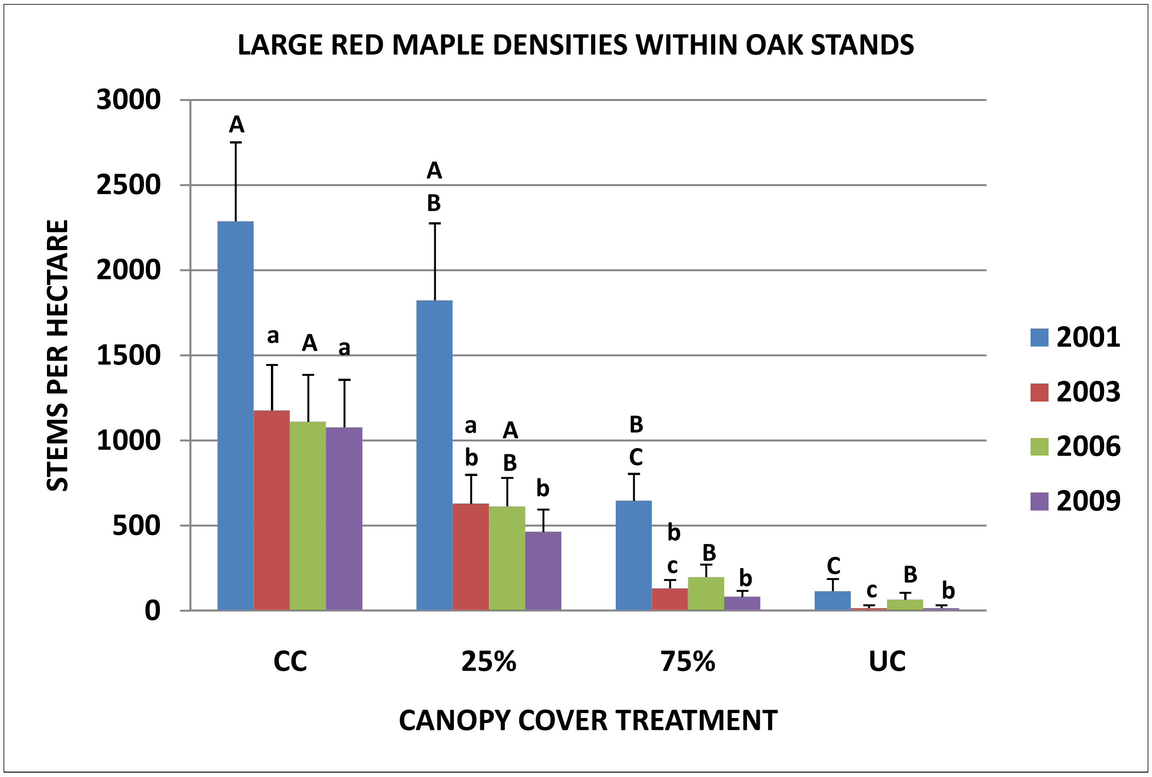

Figure 21. Large red maple genet densities within oak stands by year. Canopy cover treatment codes are as described in Fig. 1. Within years, means with the same letter are not statistically different among treatments based on Tukey's HSD (α = 0.05). Letters correspond to differences among canopy cover treatments within each year. Error bars represent standard error of the mean.

Objective 2: Response of Natural Oak Regeneration to Prescribed Fire

Density of natural oak regeneration in all size classes was greater within oak sites than pine sites (Fig. 22-23). Small oak density within oak stands increased in 25% cover treatments, but decreased in clearcut, 75% cover, and uncut control treatments following Fire 1 (Fig. 22). Small oak density in oak stands increased substantially after Fire 2 in clearcut and 25% cover treatments and decreased substantially after Fire 1 in 75% cover and uncut control treatments (Fig. 22). Reductions in oak stems per hectare were statistically different in 75% cover (P = 0.0005) and uncut control treatments (P = <0.0055) following Fire 1 (Table 4). Small oak densities in oak stands increased in all but 75% canopy treatments following Fire 2 (Fig. 22). Increases in Small oak stems per hectare were statistically significant in clearcut (P = 0.0227) and 25% cover (P = 0.0004) treatments (Table 5).

Small natural oak densities within pine stands decreased in all but 25% cover treatments following Fire 1 (Fig. 23), but no decreases were statistically different (Table 4). Small natural oak stems per hectare increased within clearcut treatments and decreased in 75% cover and uncut control treatments following Fire 2 (Fig. 23). Reductions in oak stems per hectare were only statistically different from 0 in 75% cover plots (P = 0.006) (Table 5).

Within oak stands, Medium natural oak densities in 25% cover treatments were higher than densities in other canopy cover treatments in all years (Fig. 24). Stem densities in clearcut and 75% cover treatments did not differ in any sampling year, nor did 75% cover and uncut control treatments (Fig. 24). Medium natural oak densities within oak stands decreased statistically in all canopy cover treatments following both fires, but were reduced to a greater degree following Fire 2 in all but uncut control treatments where decreases were not statistically different from 0 (P = 0.0658) (Fig. 24) (Tables 4-5).

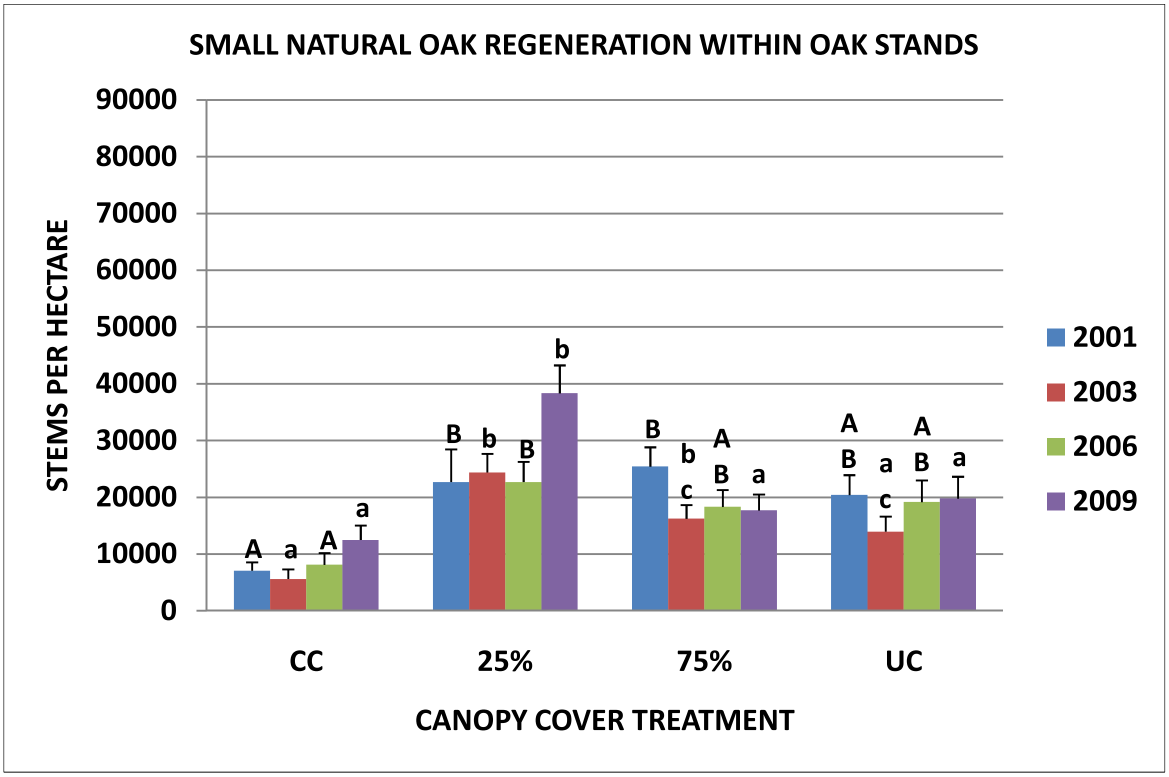

Figure 22. Small natural oak regeneration genet densities within oak stands by year. Canopy cover treatment codes are as described in Fig. 1. Within years, means with the same letter are not statistically different among treatments based on Tukey's HSD (α = 0.05). Letters correspond to differences among canopy cover treatments within each year. Error bars represent standard error of the mean.

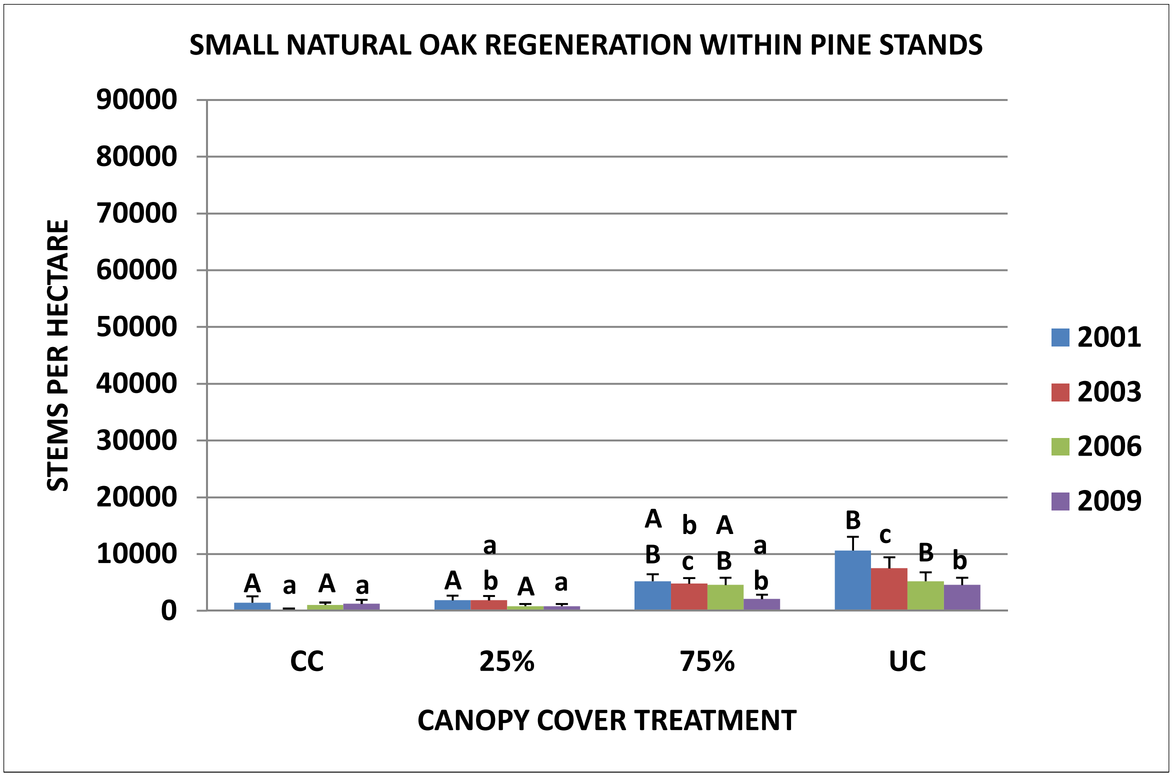

Figure 23. Small natural oak regeneration genet densities within pine stands by year. Canopy cover treatment codes are as described in Fig. 1. Within years, means with the same letter are not statistically different among treatments based on Tukey's HSD (α = 0.05). Letters correspond to differences among canopy cover treatments within each year. Error bars represent standard error of the mean.

Table 4. Natural oak regeneration stems per hectare by size class, site type, and canopy cover treatment. Bold P-values indicate statistical differences between pre-burn and post-burn densities following Fire 1 based on one-tailed t-tests at α= 0.05 significance. N = 48 sampling plots per canopy treatment.

SIZE CLASS	SITE	CANOPY TREATMENT	STEMS PER HECTARE 2001	2003	DIFFERENCE FIRE 1	P-VALUE	PERCENT DIFFERENCE FIRE 1
SMALL	**OAK**	**CC**	7083	5625	-1458	0.4737	**-20.58%**
		25%	22708	24375	1667	0.7817	**7.34%**
		75%	25417	16250	-9167	**0.0005**	**-36.07%**
		UC	20417	13958	-6458	**0.0055**	**-31.63%**
	PINE	**CC**	1458	208	-1250	0.2779	**-85.73%**
		25%	1875	1875	0	1	**0.00%**
		75%	5208	4792	-417	0.7097	**-8.01%**
		UC	10625	7500	-3125	0.2899	**-29.41%**
MEDIUM	**OAK**	**CC**	10610	4443	-6167	**<0.0001**	**-58.12%**
		25%	23542	11605	-11937	**<0.0001**	**-50.71%**
		75%	6433	2255	-4178	**<0.0001**	**-64.95%**
		UC	1790	133	-1658	**0.0025**	**-92.63%**
	PINE	**CC**	1592	199	-1393	**0.0278**	**-87.50%**
		25%	4178	663	-3515	**<0.0001**	**-84.13%**
		75%	2188	398	-1790	**0.0004**	**-81.81%**
		UC	1658	332	-1326	**0.0168**	**-79.98%**
LARGE	**OAK**	**CC**	182	66	-116	0.2905	**-63.74%**
		25%	50	50	0	1	**0.00%**
		75%	17	0	-17	0.3224	**-100.00%**
		UC	0	0	0	.	**.**
	PINE	**CC**	33	33	0	.	**0.00%**
		25%	133	33	-100	**0.0324**	**-75.19%**
		75%	17	0	-17	0.3224	**-100.00%**
		UC	33	0	-33	0.1595	**-100.00%**

Table 5. Natural oak regeneration stems per hectare by size class, site type, and canopy cover treatment. Bold P-values indicate statistical differences between pre-burn and post-burn densities following Fire 2 based on one-tailed t-tests at α= 0.05 significance. N = 48 sampling plots per canopy treatment.

SIZE CLASS	SITE	CANOPY TREATMENT	STEMS PER HECTARE 2006	2009	DIFFERENCE FIRE 2	P-VALUE	PERCENT DIFFERENCE FIRE 2
SMALL	**OAK**	**CC**	8125	12500	4375	**0.0227**	**53.85%**
		25%	22708	38333	15625	**0.0004**	**68.81%**
		75%	18333	17708	-625	0.7848	**-3.41%**
		UC	19167	19792	625	0.7568	**3.26%**
	PINE	**CC**	1042	1250	208	0.7427	**19.96%**
		25%	833	833	0	1	**0.00%**
		75%	4583	2083	-2500	**0.006**	**-54.55%**
		UC	5208	4583	-625	0.5373	**-12.00%**
MEDIUM	**OAK**	**CC**	6366	2056	-4310	**<0.0001**	**-67.70%**
		25%	18237	6963	-11273	**<0.0001**	**-61.81%**
		75%	4775	1592	-3183	**0.0003**	**-66.66%**
		UC	1260	199	-1061	0.0658	**-84.21%**
	PINE	**CC**	332	265	-67	0.6595	**-20.18%**
		25%	1989	1592	-398	0.4366	**-20.01%**
		75%	464	663	199	0.3712	**42.89%**
		UC	398	398	0	1	**0.00%**
LARGE	**OAK**	**CC**	50	83	33	0.42	**66.00%**
		25%	33	0	-33	0.1595	**-100.00%**
		75%	0	0	0	.	**.**
		UC	0	0	0	.	**.**
	PINE	**CC**	33	0	-33	0.1595	**-100.00%**
		25%	33	33	0	1	**0.00%**
		75%	0	0	0	.	**.**
		UC	0	0	0	.	**.**

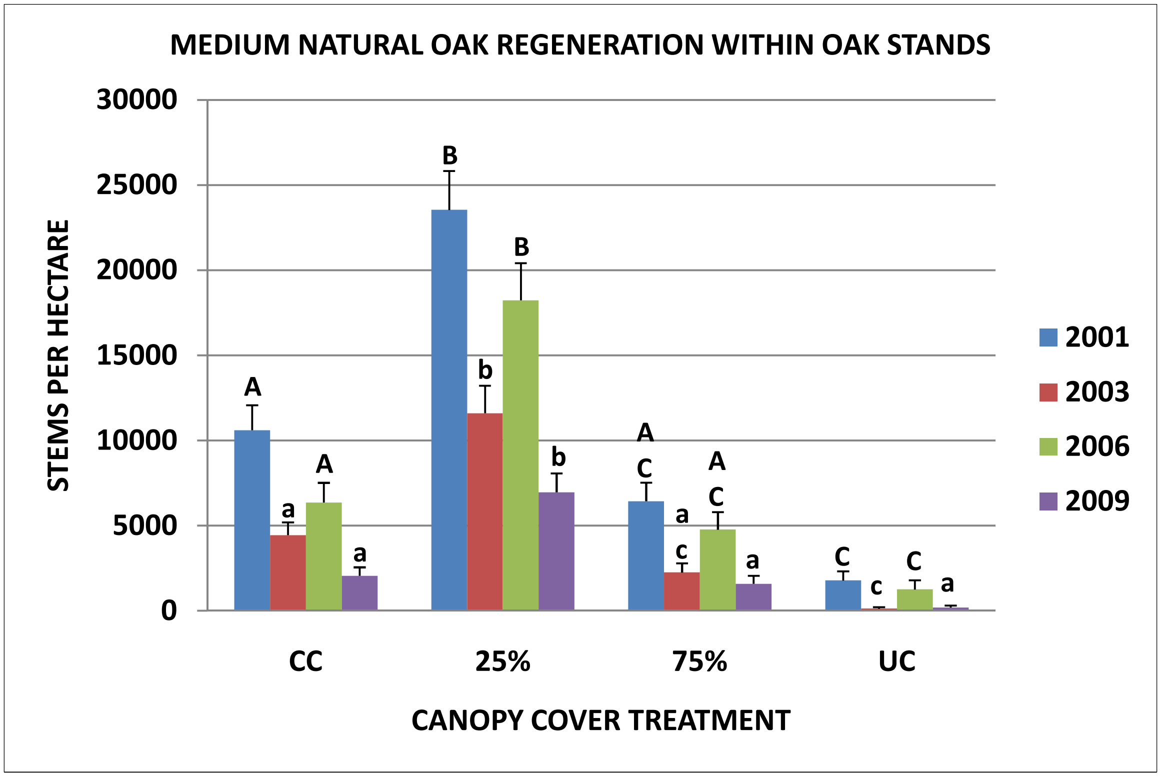

Figure 24. Medium natural oak regeneration genet densities within oak stands by year. Canopy cover treatment codes are as described in Fig. 1. Within years, means with the same letter are not statistically different among treatments based on Tukey's HSD (α = 0.05). Letters correspond to differences among canopy cover treatments within each year. Error bars represent standard error of the mean.

Medium natural oak densities within pine stands were highest in 25% cover plots in all sampling years (Fig. 25). Medium oak stems per hectare were reduced severely in all canopy treatments following Fire 1 (Table 4), but decreased to a lesser degree in clearcut and 25% canopy treatments following Fire 2 (Fig. 25). Natural oak densities increased in 75% cover treatments following Fire 2 (Fig. 25).

Large natural oak regeneration densities were higher within oak stands than within pine stands in clearcut and 25% cover treatments in all sampling years, but no Large oak stems were sampled in 75% cover or uncut control treatments after 2001 (Fig. 26). Large natural oak regeneration densities in oak stands decreased in clearcut and 75% canopy treatments, but were not reduced in 25% cover treatments following Fire 1 (Fig. 26). Large oak stems per hectare increased in clearcut treatments following Fire 2 (Fig. 26). Differences in Large natural oak densities following both fires were not statistically significant in any canopy treatment (Tables 4-5).

Within pine stands, no Large natural oak regeneration stems were sampled after 2001 in 75% cover or uncut control treatments (Fig. 27). Decreases in Large natural oak densities in 25% cover treatments were statistically significant following Fire 1 (Table 4).

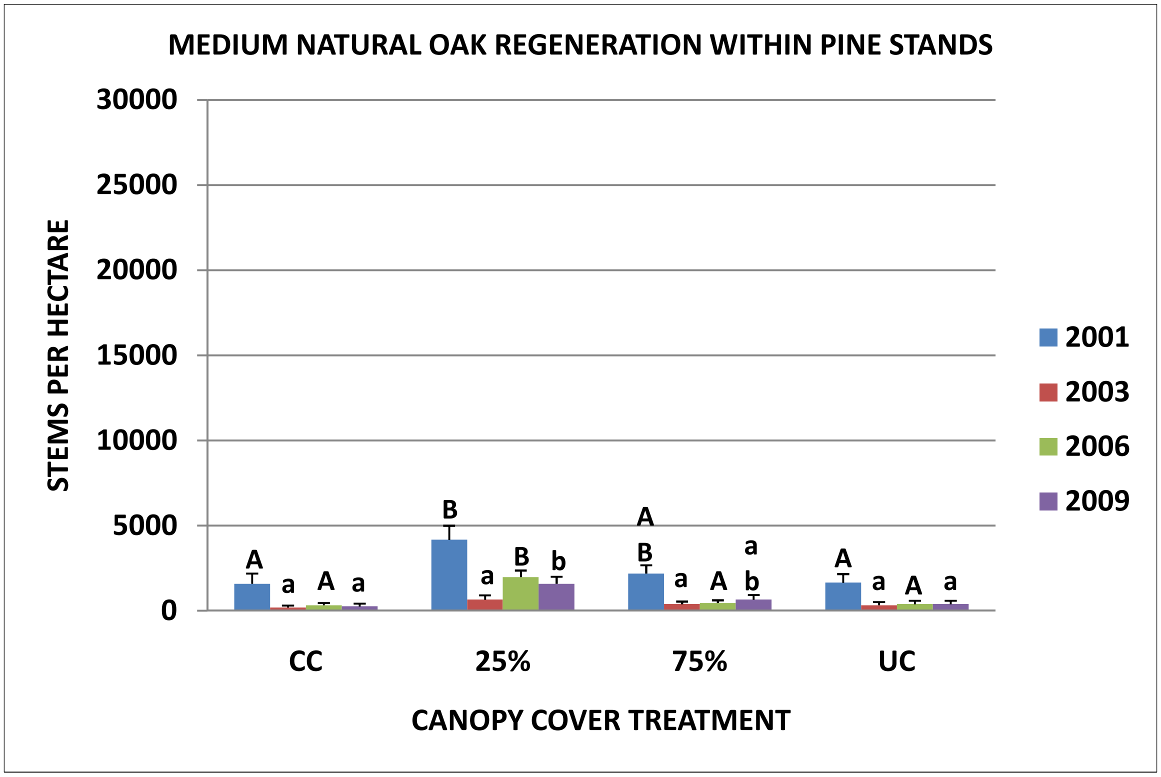

Figure 25. Medium natural oak regeneration genet densities within pine stands by year. Canopy cover treatment codes are as described in Fig. 1. Within years, means with the same letter are not statistically different among treatments based on Tukey's HSD (α = 0.05). Letters correspond to differences among canopy cover treatments within each year. Error bars represent standard error of the mean.

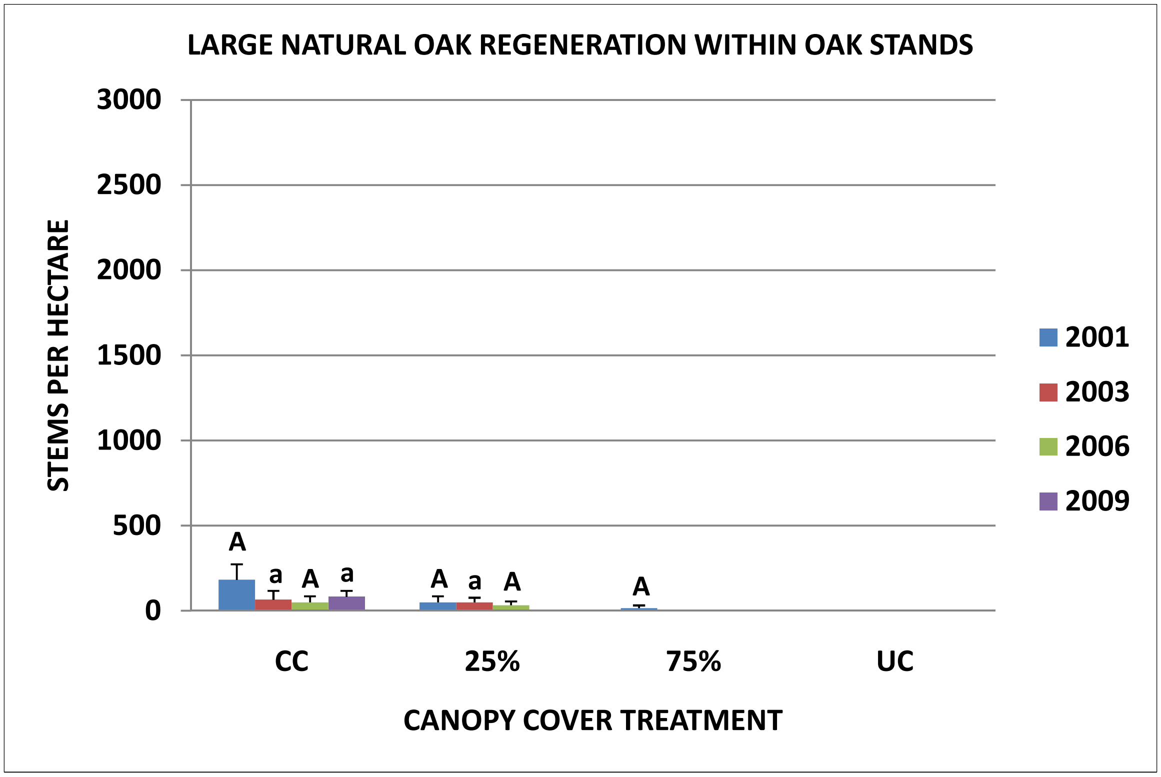

Figure 26. Large natural oak regeneration genet densities within oak stands by year. Canopy cover treatment codes are as described in Fig. 1. Within years, means with the same letter are not statistically different among treatments based on Tukey's HSD (α = 0.05). Letters correspond to differences among canopy cover treatments within each year. Error bars represent standard error of the mean.

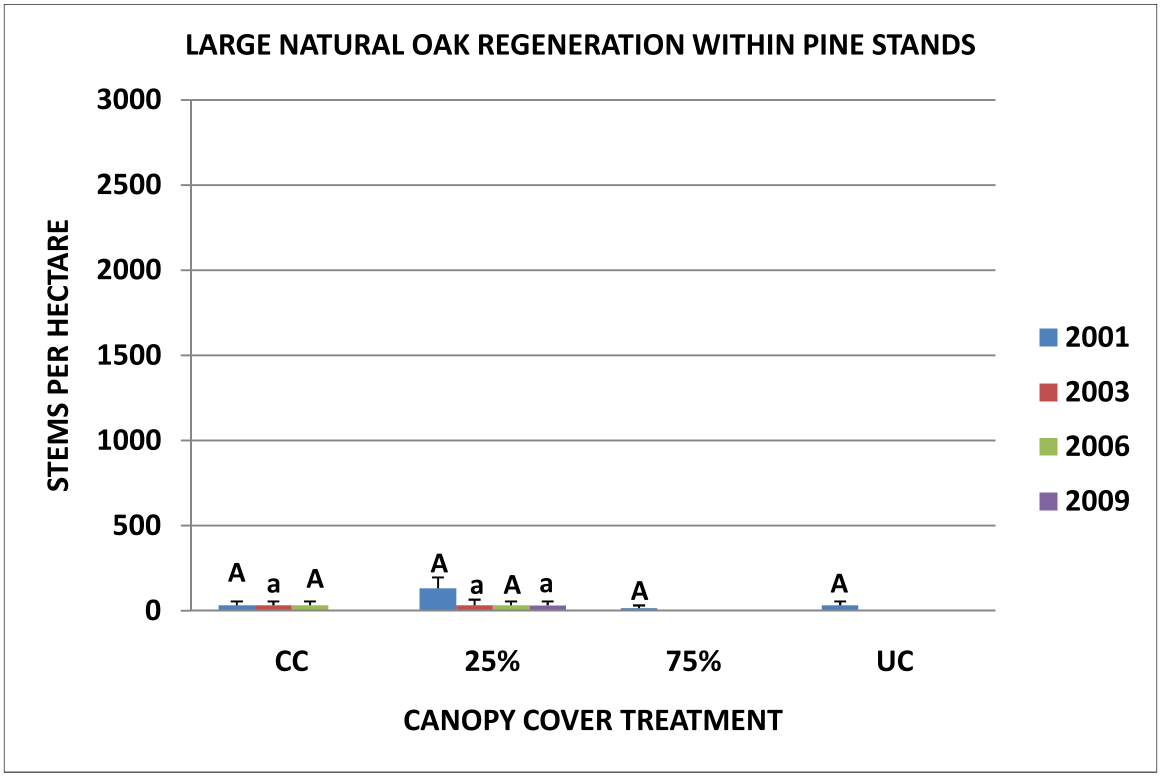

Figure 27. Large natural oak regeneration genet densities within pine stands by year. Canopy cover treatment codes are as described in Fig. 1. Letters correspond to differences in each year. Within years, means with the same letter are not statistically different among treatments based on Tukey's HSD ($\alpha = 0.05$). Letters correspond to differences among canopy cover treatments within each year. Error bars represent standard error of the mean.

Objective 3: Relationships between post-burn planted oak sprout height and other factors

Planted oak heights in 2009 were not significantly related to 2009 canopy cover or 2008 fire temperatures. Pearson correlations indicated weak relationships between 2009 height and 2009 canopy cover ($r = 0.256$, $P = <0.0001$), and between 2009 height and Fire 2 temperature ($r = 0.223$, $P = <0.0001$). Multiple regression using 2006 height ($P = <0.0001$), 2009 canopy cover ($P = 0.1775$), and Fire 2 temperature ($P = 0.025$) predict planted oak sprout height in 2009, did little to improve R^2 values ($R^2 = 0.6229$) over a simple linear regression, with pre-burn oak height in 2006 explaining variation in post-burn height in 2009 ($R^2 = 0.6204$) (Fig. 28). Pre-burn height in 2001 explained only 33% of the variation in post-burn height in 2003 following Fire 1 (Fig. 29).

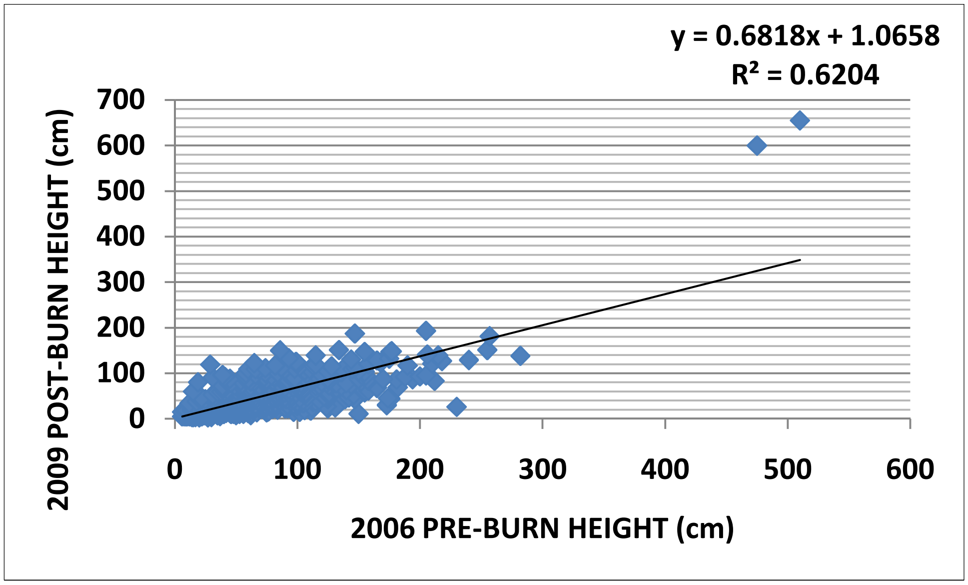

Figure 28. Simple linear regression relating pre- and post-burn planted oak heights after Fire 2 pooled across both site types.

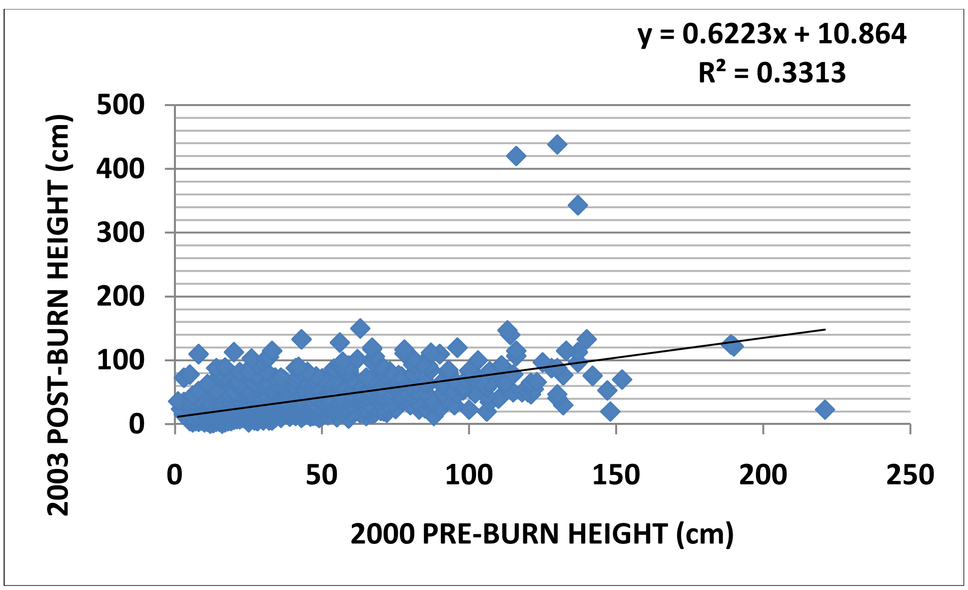

Figure 29. Simple linear regression relating pre- and post-burn planted oak heights after Fire 1 pooled across both site types.

DISCUSSION

Objective 1: Planted Northern Red Oak Sprout Heights

The hypothesis that planted oak stems would exhibit greater height growth following Fire 2 than Fire 1 was supported for oak stems planted within pine stands, but not supported for oak stems planted within oak stands.

Height growth of planted oaks following Fire 2 was less than following Fire 1 in all canopy treatments within oak stands. Brose (2008) recommended shelterwood harvests that reduce canopy cover to 50% or less in order to stimulate growth in oak regeneration, thereby increasing survivorship and promoting rapid growth following prescribed fire. Height growth was greatest in clearcut and 25% cover treatments for all years, but differences in height growth from 2003 to 2009 were also greatest within these treatments. Stems within these treatments had more height to recover following Fire 2 and did not grow as rapidly. Height growth of planted oaks may have been inhibited in these canopy treatments in oak stands by excessive competition from Large red maple regeneration. This was difficult to test statistically, however, due to the low number of surviving planted oaks in these treatments. Clearcut and 25% cover treatments within oak stands contained the highest densities of Large red maple regeneration of the four canopy treatments. Large red maple densities were not reduced statistically following Fire 2, and had effectively increased canopy cover within these treatments to above 70% by 2009.

Planted oak height growth within pine stands was greater following Fire 2 than following Fire1 in all canopy treatments. The increase in growth rate following the second fire in all levels of canopy cover demonstrates the ability of these planted oak to sprout vigorously, in the absence of midstory competition, following disturbance, even 19 growing seasons after establishment.

By 2009, height of planted oaks in each canopy treatment within pine stands exceeded that observed in corresponding canopy treatments within oak stands. This difference in height growth may be due to the lack of competing vegetation in the midstory and understory of pine stands (Hartman et al., 2005). The absence of red maple and other competitors in the midstory within pine stands likely allows increased height growth of oak stems over stems planted in oak stands.

There have been substantial differences between caged and uncaged oak stems since this project began, due to severe browsing pressure from white-tailed deer (*Odocoileus virginianus*) (Buckley et al., 1998; Hartman et al., 2005). Height of uncaged planted oak seedlings in both oak and pine stands have rarely exceeded 30 cm in any sampling year since 2001, and differences between canopy treatments have become smaller since Fire 2. Uncaged oak heights in 2009 were statistically lower than 2003 heights in all canopy treatments within oak stands, due to a combination of browsing pressure and competition from other woody stems. These stems are unlikely to escape the understory.

Obective 2: Response of Red Maple and Natural Oak Regeneration to Prescribed Fire

Over the history of this study, the pine stands have contained substantially fewer red maple and other competing stems in all size classes than in oak stands (Buckley et al., 1998; Hartman et al., 2005). Red maple samaras are among the lightest of the *Acer* family, and are easily dispersed by wind (Abrams, 1998). Because of their light weight, red maple seeds have low energy reserves, which may prevent radicles from penetrating pine litter to mineral soil and prevent establishment. There were no overstory red maple stems found within pine stands prior to thinning treatments in 1991, which indicates that red maple has not fared well on these sites since pine was planted by the CCC in the 1930s (Hartman et al. 2005). Since red maple densities were already extremely low within pine stands, reductions following both prescribed fires were rarely statistically significant in any canopy cover treatment.

Within oak stands, the hypothesis that red maple densities would be reduced more by the second fire than by the first was not supported. Both fires reduced Medium and Large red maple densities across all canopy treatments, but densities were reduced to a greater degree following Fire 1, which had lower measured temperatures than Fire 2. Medium red maple densities across all canopy treatments were reduced by an average of 50 percent following Fire 1 and by an average of 35 percent following Fire 2. Although Medium red maple densities were reduced more by Fire 1 than Fire 2, statistically significant reductions in all canopy cover treatments following Fire 2 indicate that the second fire has had a continued and compounding negative impact. Similarly, reductions in understory red maple density, following single and repeated burns, were also reported by Alexander et al. (2008).

Large red maple densities in all size classes were reduced by 70% following Fire 1 and by 40% following Fire 2. Reductions in Large red maple densities following both fires were lowest in clearcut and 25% canopy treatments, where Large size class stems densites were highest. Large red maple densities were reduced in all canopy cover treatments following Fire 2, but reductions did not approach reductions in corresponding treatments following Fire 1. Many of the larger surviving stems in all canopy treatments were stump sprouts, which emerged following the removal of midstory saplings following thinning operations in 1991, when canopy treatments were implemented. Red maple stump sprouts can exhibit rapid, sustained height growth for years following disturbance (Blankenship and Arthur, 2006; Green et al. 2010). These stems had 10 years to develop between initial thinning treatments and the first prescribed fire.

Densities may have been reduced more following Fire 1 because of high mortality among stressed, ill-formed, or diseased stems, leaving only the most robust, well-established stems, which then had six growing seasons to recover before Fire 2. Many of these stems, especially in clearcut treatments, have grown into dominant or co-dominant canopy positions, and are now large enough to survive periodic low-intensity fires. The substantial increases in small red maple stems in all canopy treatments between 2003 and 2009 demonstrate not only that red maple genets continue to propogate in from the surrounding forest, but also that, even after two prescribed fires, the root systems of top-killed Medium or Large stems are large and robust enough to send up multiple, fast-growing shoots, which continue to compete with oak (Gilbert et al., 2003). Reducing these robust stems may require continued repeated burning, which unfortunately, could also prove detrimental to oak (Alexander et al., 2008; Blankenship and Arthur, 2006).

The hypothesis that natural oak regeneration stem densities would increase to a greater degree following Fire 2 than following Fire 1 was not supported. The reasoning behind this hypothesis was that natural oak regeneration would benefit from a second fire by decreased competition for light and resources from red maple and other competitors (Iverson et al., 2008), and that natural oak regeneration would possess the ability to sprout more vigorously after an additional six years of development (Brose and Van Lear, 2004). It was predicted that natural oak regeneration sprouts would exhibit more rapid height growth following the second fire, therefore, recruiting into the larger sizes classes more quickly than following Fire 1. However, Medium natural oak densities within oak stands decreased to a greater degree following Fire 2 than following Fire 1 in clearcut and 25% cover treatments, where natural oak densities were highest in all sampling years. Within pine stands, Medium natural oak regeneration was decimated following Fire 1 with reductions of at least 80 percent in all canopy treatments. Medium natural oak densities were less negatively affected in clearcut and 25% cover treatments following Fire 2, but still declined an additional 20 percent. Medium natural oak density increased by 199 stems per hectare in 75% cover plots following Fire 2, but this increase seems unsubstantial when compared to the 1790 stems per hectare decrease in these plots following Fire 1.

Both fires were detrimental to Large natural oak regeneration in all site types and canopy cover treatments. A few natural oak stems were able to recruit to the Large size class in clearcuts within oak stands following Fire 2, which, by 2009, were the only canopy cover treatment plots within oak stands containing Large natural oak regeneration. All Large natural oak in 25% cover treatments within pine stands survived the second fire, which, like Large red maple regeneration, indicates these stems have become large enough to be unaffected by low-intensity prescribed fire.

Oak sites contained higher densities of natural oak regeneration in all size classes than did pine stands across all canopy cover treatments and sampling years, likely because of the lack or mature oak trees capable of producing seed within pine sites. Acorns may have been brought into pine sites and cached by birds and squirrels, but likely in far fewer numbers than red maple seeds were dispersed into pine stands by wind. However, densities of natural oak regeneration were higher than red maple regeneration densities within pine stands for all size classes in all canopy treatments following each fire. This trend indicates a much higher rate of establishment and growth for oak than for red maple within pine stands.

Within oak stands, the response of natural oak regeneration to two prescribed fires has generally mirrored the response of red maple regeneration in all size classes and canopy cover treatments. These results are comparable to those obtained in other prescribed fire studies on the Cumberland Plateau (Arthur et al., 1998; Gilbert et al, 2003; Blankenship and Arthur, 2006; Gilbert, 2010). When red maple densities decreased, natural oak densities also decreased by a similar proportion. Medium natural oak densities within oak stands were greater than or nearly equal to red maple densities in clearcut and 25% cover treatments through 2006, but Medium red maple densities became greater than oak densities in both treatments following the second fire. There was a smaller reduction in Medium red maple stems per hectare than in Medium natural oak following Fire 2. This result is the opposite of what was expected following Fire 2, and may be explained by the continued dominance of Large red maple stems in these canopy cover treatments. Red maple regeneration has maintained much higher densities than natural oak in all size classes within 75% cover and uncut control treatments. By 2009, canopy cover in clearcut and 25% cover treatments were in excess of 70 percent and not statistically different from 75% cover treatments. The increase in canopy cover, caused by red maple regeneration large enough to survive and to resprout vigorously following prescribed fire, has likely limited the growth of both natural and planted oak sprouts through competition for light (Alexander et al., 2008), while allowing red maple regeneration in the smaller size classes to establish and develop in favorable, shaded conditions (Abrams, 1998; 2005).

Objective 3: Relationships between post-burn planted oak sprout height and other factors

Pre-burn height of planted oak exhibited the strongest relationship with post-burn sprout height following Fire 2. Greater sprout heights were achieved on both site types in treatment plots with less canopy cover, and the greatest sprout heights were achieved within pine stands. Statistical differences in percent canopy cover continue within pine stands, although percent cover has increased substantially since canopy cover treatments were implemented in 1992. By 2009, trees in dominant canopy positions on all sites (i.e., red oak, red pine, or red maple) had grown too large to be affected by low-intensity prescribed fire, which may explain why percent canopy cover remained high following Fire 2. Original canopy cover levels following thinning in 1992 would likely yield a stronger relationship with 2009 oak sprout height than 2009 canopy levels. Opening the canopy to levels comparable to 1992 levels would take additional mechanical thinning which may not be economically viable. The use of additional prescribed fires to reduce canopy cover would require multiple, higher-intensity burns, which would likely prove more detrimental to the oak regeneration on these sites than to canopy trees.

It was thought that red maple and other competitors of oak may be reduced to a greater degree in plots with higher fire temperatures than in plots where fire temperatures were lower, thereby allowing increased height growth in planted oak sprouts. This assumption was not supported. The weak relationship between Fire 2 temperature and post-burn planted oak sprout height may be due the wide variation in individual sprout growth within a given plot. One measurement of fire temperature per plot may be too broad to explain individual growth. Fire temperatures were likely variable within each plot, and may have had different effects on individual seedlings. However, most oak stems were top killed regardless of Fire 2 temperature, which may further explain the weak relationship between the two while giving further credence to the importance of pre-burn oak height (Alexander et al., 2008; Brose, 2008).

CONCLUSIONS

The increased height of caged planted oak sprouts within pine stands following two prescribed fires demonstrates that northern red oak has the ability to sprout vigorously following disturbance, even 19 growing seasons after planting. These results were achieved in pine stands, which have consistently contained statistically fewer competitors of oak in the midstory and understory compared to oak stands. Managers regenerating oak under pine stands, as suggested by Hartman et al. (2005), may not have the need to reduce understory competitors in order stimulate through burning, especially if competitors of oak are absent from the midstory.

Within oak stands, planted oak sprouts exhibited a decrease in height growth following Fire 2 when compared with post-Fire 1 heights. This decrease in height growth was likely compounded by the continued, excessive competition from large red maple regeneration that arose as stump sprouts from stems originally cut in 1992. Red maple regeneration had 10 years to develop before the first prescribed burn was implemented in 2002. Red maple stems were initially reduced by the first fire, but have since rebounded and continue to dominate the understory and midstory of oak stands.

The two prescribed fires had a cumulative impact on Medium red maple regeneration, statistically reducing its densities following each fire. Overall, the two prescribed fires reduced Medium red maple densities by 46-74% across all canopy treatments. Oak has not benefited from these reductions in understory competition, however, because it is still overtopped by the red maple midstory. Prior to Fire 2, Medium natural oak regeneration densities were higher than Medium red maple densities in canopy cover treatments with less cover. By 2009, Medium natural oak regeneration densities within oak stands had fewer stems per hectare than red maple regeneration in the same size class.

Low-intensity prescribed burns implemented more frequently than in this study may help to reduce large red maple regeneration. More frequent burns, however, may also have an adverse effect on oak regeneration. Burning just after, or just prior to, canopy treatment implementation may prevent red maple stump sprouts from developing into the large midstory stems capable of surviving prescribed fires, as encountered in this experiment.

Prescribed fire beneath shelterwoods to stimulate oak growth in areas with large deer populations may not be feasible, especially if oak regeneration has achieved heights greater than browsing height (~ 1.6 m). Burning will bring oak regeneration sprouts down to browse height. Oak regeneration has little chance of developing into advanced regeneration capable of reaching the canopy when large deer populations are present, as evidenced by caged versus uncaged planted oak sprout heights in both site types and across all treatments in this experiment.

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VITA

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