Available online at www.sciencedirect.com
ScienceDirect
Forest Ecology and Management 255 (2008) 3035–3050
Forest Ecology and Management
www.elsevier.com/locate/foreco

Thinning, fire, and oak regeneration across a heterogeneous landscape in the eastern U.S.: 7-year results

Louis R. Iverson *, Todd F. Hutchinson, Anantha M. Prasad, Matthew P. Peters

Northern Research Station, U.S.D.A. Forest Service, 359 Main Road, Delaware, OH 43015, USA

Received 14 June 2007; accepted 11 September 2007

Abstract

We document an increase in oak and hickory advance regeneration, depending on landscape position, in the sixth year following mechanical thinning and repeated prescribed fires in southern Ohio, USA. Oak-dominated communities provide a multitude of human and natural resource values throughout the eastern United States, but their long-term sustainability is threatened throughout the region by poor regeneration. This study was established to assess regeneration following midstory thinning (late 2000) and prescribed fire application (2001 and 2005) at two sites in southern Ohio. Each of the four 20+ ha treatment units (two thin and burn, two untreated controls) were modeled for long-term moisture regime using the integrated moisture index (IMI), and a 50 m grid of sampling points was established throughout the units. Vegetation and canopy openness were sampled at each gridpoint before and after treatments, in 2000, 2001, 2004, and 2006. The thin and burn treatment generally resulted in more advance regeneration (>50 cm height) of oak and hickory. The second fires in 2005 created additional landscape heterogeneity by causing variable tree mortality, and thus canopy openness, across the IMI gradient. The drier landscape positions generally had more intense fires, more canopy openness, and more oak and hickory advance regeneration; several other tree species also exhibited marked landscape variation in regeneration after treatments. Though advance regeneration of several competing species became abundant after the initial treatments, the second fires reduced the high densities of the two major competitors, *Acer rubrum* and *Liriodendron tulipifera*. Two simple models were developed: (1) a model of oak "competitiveness" based on the plot data related to advance regeneration of oaks and competitors and (2) a model estimating the probability of a plot becoming 'competitive for oak' based on canopy openness, IMI class, and number of oak and hickory seedlings present. For dry or intermediate sites with at least 5000 oak and hickory seedlings/ha, opening the canopy to 8.5–19% followed by at least two fires should promote oak and hickory to be 'competitive' over about 50% of the area. However, no appreciable oak and hickory regeneration developed on mesic sites. Overall, these results suggest promise for partial harvesting and repeated fires as a management strategy to reverse the accelerating loss of oak dominance in the central hardwoods region.
Published by Elsevier B.V.

Keywords: Oak regeneration; Central hardwoods region; Thinning; Prescribed fire; Topography; Ohio; Oak (*Quercus*); Hickory (*Carya*); Maple (*Acer*); Yellow-poplar (*Liriodendron tulipifera*); Integrated moisture index

1. Introduction

A large portion of the central hardwoods region (CHR) of eastern U.S. forests is undergoing a conversion from dominance by oak–hickory (*Quercus* and *Carya*) to maple (*Acer*) and other shade-tolerant and/or mesophytic species (Abrams, 2003). U.S. Forest Service forest inventories of Ohio from 1968 and 1991 (Kingsley and Mayer, 1970; Dennis and Birch, 1981; Griffith et al., 1993) indicate that the proportion of total volume in oak and hickory has declined substantially relative to maple, yellow-poplar (*Liriodendron tulipifera*), and black cherry (*Prunus serotina*). The relative importance of several oak and hickory species in Ohio declined by at least 22% during this same period while maple and yellow-poplar increased by at least 38% in total volume. In Pennsylvania, forest types dominated by red maple increased 22% between 1989 and 2000 (McWilliams et al., 2004). This trend is evident throughout much of the CHR (Iverson et al., 1989; Nowacki and Abrams, 1992; SAMAB, 1996).

Mature closed-canopied forests in the CHR are usually characterized by an oak-dominated canopy, even in relatively mesic landscape positions, and small oak seedlings are often relatively abundant, at least on drier sites. However, oak advance regeneration (large seedlings and saplings) is typically

* Corresponding author at: Tel.: +1 740 368 0097; fax: +1 740 368 0152.
E-mail address: liverson@fs.fed.us (L.R. Iverson).

0378-1127/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.foreco.2007.09.088

sparse. These compositionally unstable oak forests have been documented thoroughly across the eastern United States (e.g., Abrams, 2003). Though oak regeneration has been an object of concern and study for several decades, increasingly poor oak regeneration continues to prompt large scientific efforts to assess the problem and search for management solutions (e.g., Loftis and McGee, 1993; Johnson et al., 2002; McShea and Healy, 2002; Spetich, 2004), including a better understanding of the historic role of fire and the use of prescribed fire in oak forests (Brose et al., 1999, 2001; Iverson et al., 2004a; Dickinson, 2006).

Several factors contribute to poor oak regeneration. In the pervasive closed-canopy conditions, the shade-intolerant oaks are out-competed by more shade-tolerant species (Hilt, 1985; Loftis and McGee, 1993). When light is not limiting (e.g., after a clearcut), faster-growing species such as yellow-poplar often out-compete oak, particularly on higher-quality sites (Beck, 1990; Marquis, 1990). The success of oak regeneration after a canopy-opening disturbance usually varies across a soil moisture gradient, with oak regeneration competitive only under dry conditions (Iverson et al., 1997). Thus, a landscape-level approach to assessing treatment effects across a moisture gradient is important to provide an evaluation at the scale of typical forest management units (Boerner, 2006).

Prior to Euro-American settlement (ca. 1800), oaks were the dominant tree species across most of the Allegheny Plateau of southern Ohio (Beatley and Bartley, 1959; Dyer, 2001). Dendrochronology fire history studies from the period ca. 1870–1935 have shown that fire occurred frequently (~10-year fire interval) as forests were regenerating after widespread and exploitive timber harvesting in the 1800s (Sutherland, 1997; McEwan et al., 2007). Fire control was instituted in 1923 and became very effective by the mid-1930s (Leete, 1938). It has been hypothesized that the dramatic decrease in fire frequency has created large aberrations in several facets of forest ecology, including the widespread establishment of maples and other fire-sensitive species that now threaten the sustainability of oak dominance (Sutherland and Hutchinson, 2003).

A previous study (Hutchinson et al., 2005) in southern Ohio showed that after many years of fire exclusion, simply returning several low-intensity prescribed fires to mature oak forests did not consistently increase canopy openness and generally did not stimulate the development of oak advance regeneration. Therefore, we initiated a study to assess the effects of mechanical thinning in addition to prescribed fire as a management tool to improve oak regeneration in our region. As one site (The Ohio Hills) of the national Fire and Fire Surrogates Study (FFS) (Youngblood et al., 2005), we are assessing these treatments as possible means of reducing the abundance of shade-tolerant species and developing oak advance regeneration (Iverson et al., 2004a; Rebbeck et al., 2004). Albrecht and McCarthy (2006) evaluated regeneration on plots for four post-treatment years after the thinning and the initial prescribed fire. They found that oak and hickory seedlings (<140 cm) responded neither positively nor negatively to any treatment (burn only, thin only, thin + burn) during that period. However, the abundant sprouting and establishment of competitors (e.g., *Acer rubrum*, *L. tulipifera*, *Nyssa sylvatica*, *Sassafras albidum*) into the advance regeneration layer further reduced the competitive status of oak and hickory. Albrecht and McCarthy (2006) suggested that additional fire(s) would likely be necessary to reduce the abundance and size of competitors, and thus potentially favor oak and hickory regeneration.

Microclimatic factors, such as solar radiation, air temperature, humidity, soil temperature, and soil moisture, vary substantially across landscapes with heterogeneous topography (Kang et al., 2000). In turn, these factors influence the structure and composition of forest vegetation (Iverson et al., 1997; Boerner, 2006). Human-controlled factors, such as timber harvesting, also can have profound influences on microclimate (Chen et al., 1999; Zheng et al., 2000).

The primary objective of this study, as a component of the FFS Ohio Hills study, is to measure the effects of thinning and repeated prescribed fires (2001 and 2005) on canopy openness and tree regeneration over a 7-year period, with emphasis on the response of oaks and hickories relative to competing species. We stratified our sites by the integrated moisture index (IMI; Iverson et al., 1997) to describe landscape variation on the effects of thinning and burning. We sampled canopy openness and regeneration four times in a 50 m grid across the heterogeneous landscapes. We used the resultant information to map the potential for oak and hickory regeneration success based on the advance regeneration present 6 years after treatments began.

2. Methods

2.1. Site description

Our study is located in Vinton County, Ohio, at two of the three Ohio Hills FFS replicates. The Raccoon Ecological Management Area (REMA) replicate site (39°12′41″N, 82°23′09″W) is located within the Vinton Furnace Experimental Forest, which has been the site of silviculture and forest ecology studies and demonstrations since the early 1950s. The Zaleski (ZAL) replicate site (39°21′17″N, 82°22′06″W) lies within Zaleski State Forest and is managed by the Ohio Department of Natural Resources, Division of Forestry.

The area lies in the unglaciated Allegheny Plateau physiographic region and is characterized by dissected topography (narrow ridges and valleys) and less than 100 m of local relief. The upland forests are mostly a complex mosaic of mixed-oak and oak-hickory forests, grading into mixed-mesophytic communities in ravines and other sheltered locations (Beatley and Bartley, 1959). The current overstory regenerated ca. 1850–1900 after being harvested for charcoal to fuel nearby iron furnaces.

The most abundant oak and hickory species are white oak (*Quercus alba*), chestnut oak (*Q. prinus*), black oak (*Q. velutina*), scarlet oak (*Q. coccinea*), red oak (*Q. rubra*), pignut hickory (*Carya glabra*), and mockernut hickory (*C. tomentosa*). Oaks are much less abundant in the midstory and understory layers, and species composition in these layers is more strongly influenced by topographic characteristics. In all but the most dry landscape positions, red maple (*A. rubrum*) and other shade-tolerant species, such as blackgum (*N. sylvatica*), American beech (*Fagus grandifolia*), and sugar maple (*Acer saccharum*), dominate the midstory and understory strata, while oak and hickory advance regeneration is typically sparse (Sutherland and Hutchinson, 2003).

2.2. Study design

The overall FFS study design consists of four treatments on each of three replicate sites, resulting in 12 treatment units of 20–25 ha each. The four treatments are untreated control (C), mechanical thinning, prescribed burning, and a combination of thinning and burning (TB). Vegetation and soils have been sampled on ten 0.1 ha permanent plots per treatment unit (e.g., Albrecht and McCarthy, 2006). For the present study, we restricted sampling to only the C and TB units on the ZAL and REMA sites (four treatment units), but systematically sampled these units more intensively across the landscape. Gridpoints were established every 50 m throughout the units using a global positioning system (GPS). The number of gridpoints sampled per unit was 45 at ZAL C, 60 at ZAL TB, 66 at REMA C, and 71 at REMA TB. These 242 points are the basis of all analyses reported in this paper.

The integrated moisture index (IMI) was used to estimate the influence of varying topography and soils across the landscape (Iverson et al., 1997). The IMI is a GIS model (0–100 scale) of long-term moisture availability based on solar radiation (‘‘hillshade’’), position on the slope (‘‘flow accumulation’’), curvature of the landscape, and water-holding capacity of the soils. IMI is related to soil moisture (Iverson et al., 2004b) and has been used to predict forest site productivity and composition, understory vegetation, soil nutrients, and bird distributions (Iverson et al., 1996; Hutchinson et al., 1999; Dettmers and Bart, 1999; Boerner et al., 2000; Dyer, 2001). Here we categorized gridpoints into one of three IMI classes for ease in interpretation: dry (score < 35), intermediate (35–50), and mesic (>50).

2.3. Treatments

Thinning occurred from December 2000 to February 2001 and removals were concentrated in the midstory (trees 15–30 cm dbh); oaks and hickories were favored for retention. Stumps were not treated with herbicides following cutting. For the ZAL TB site, basal area was reduced from 25.5 to 18.5 m^2/ha. The density of overstory (dominant and codominant) trees was reduced from 192 to 142 stems/ha; the midstory (intermediate and suppressed) from 255–150 stems/ha. On the REMA TB unit, thinning reduced basal area from 28.0 to 22.6 m^2/ha; overstory and midstory densities were reduced from 133 to 103 and from 239 to 194 trees/ha, respectively (Daniel Yaussy, unpublished data).

The first prescribed fires were conducted on 4 (ZAL) and 5 (REMA) April 2001, several months after the mechanical thinning had occurred. Trees had not yet begun to leaf out. The entire 20+ ha units were burned. Flame lengths were generally 0.5–1 m. Thermocouples placed at every gridpoint, 25 cm above ground, were used to monitor the degree and duration of temperature increase across the landscape during those fires (Iverson et al., 2004b). The mean maximum thermocouple temperatures for ZAL TB and REMA TB were 140 and 144 °C, respectively. Animated recreations of these two fires, based on GIS extrapolation of thermocouple data across the landscapes, are available at www.fs.fed.us/ne/delaware/4153/ffs/prescribed_burn.html. These fires caused very little overstory tree mortality (Daniel Yaussy, U.S. Forest Service, unpublished data). Fine fuels (1 h) burned completely in most areas, but coarse fuels (100 and 1000 h) were generally not consumed.

The second prescribed fires were conducted in 2005, at ZAL TB on 5 April and at REMA TB on 11 April. Again, trees had not yet begun to leaf out. Drier weather conditions, coupled with the coarse fuels having cured from the thinning 4 years earlier, resulted in higher-intensity fires, with flame lengths often 1–2 m, occasionally more. At ZAL TB, the average maximum temperature recorded by the thermocouples was 211 °C and these temperatures were relatively homogeneous across the landscape. At REMA TB, the average maximum temperature was 169 °C, but fire behavior varied dramatically across the landscape from very low intensity (flame lengths 0.25 m) on the north-facing slope to very high-intensity (flame lengths often >2 m) on the southwest-facing slope, resulting in significant overstory mortality.

2.4. Canopy openness sampling

To estimate understory light transmission levels, hemispherical photographs were taken at each gridpoint in July 2000, July 2001, and July 2006, with a digital camera leveled 1.5 m above the forest floor. At each point four photographs were taken at different exposure level increments due to variability in cloud cover and canopy cover conditions. For each gridpoint, we selected one image with the best (in our opinion) exposure for analysis purposes. We then analyzed the photographs with the Gap Light Analyzer program (GLA, version 2.0; Frazer et al., 1999) to calculate canopy openness, which is the percentage of open sky seen from beneath a forest canopy given the additional influence of an effective horizon that is less than 90° (Frazer et al., 1999). The analysis is affected by variations in image thresholding (converting the color image to black [cover] and white [open]) by the analyst. To minimize analyst variations, one person performed all of the GLA analyses within each year's set of photos.

2.5. Vegetation sampling

Vegetation was sampled in all four units in 2000 (before treatment), 2001 (first growing season after thinning and the first prescribed fire), 2004 (fourth growing season after thinning and the first fire), and 2006 (second growing season after the second fire and 6 years after thinning). At each gridpoint, small seedlings (<50 cm height) of all tree species were recorded within four 2 m^2 circular plots in the cardinal directions, centered 2 m from the gridpoint. To increase the sample area for oak and hickory seedlings, we sampled an additional 8.5 m^2 plot centered on the gridpoint.

The advance regeneration, in which we include large seedlings (50–140 cm) and saplings (>140 cm height to 9.9 cm dbh) of all tree species, were recorded in a 78.5 m^2 circular plot (5 m radius) centered on the gridpoint. By the fourth growing season (2004) after the thin and burn treatment, there were dense thickets of woody stems in many areas, consisting of numerous large seedlings and saplings (e.g., yellow-poplar—*L. tulipifera*), stump sprouts (most notably red maple), and shrubs (e.g., *Rubus* spp., *Smilax rotundifolia*). Therefore, in 2004 and 2006, we were forced to reduce the area in which we sampled large seedlings (50–140 cm) of non-oak + hickory species to the four 2 m^2 seedling plots at each gridpoint; thus for those years we used different multipliers to calculate stems/ha. Throughout the study, we continued to sample large oak and hickory seedlings (50–140 cm) within the 78.5 m^2 plots. Also, for large seedlings and saplings in 2004 and 2006, we recorded each multiple-stemmed clump of sprouts as a single individual rootstock but also noted the number and size class of sprouts.

The species and basal area of overstory trees was recorded with a 10-factor basal area prism at each gridpoint in each sample year. In order to calculate overstory tree density on a per-unit-area basis, we used additional data collected in the ten 0.1 ha plots in each treatment unit.

2.6. Data analysis

2.6.1. Statistical analysis

We used several methods to summarize, analyze, and evaluate trends and treatment effects. Since the 242 gridpoints are technically pseudoreplicates within only two replicates of control and TB treatments, analysis of variance was not appropriate. Therefore, we report means and standard errors for comparative information. We graphed population trends among IMI classes for several seedling and sapling size classes of oak and hickory and also several of the major competitors. Relative abundance composition plots were constructed that showed the proportions of each species group by size class in years 2000 (before treatment) and 2006 (after treatment with thinning and burning), for the REMA and ZAL TB sites combined. We also graphed the relationship between oak and hickory advance regeneration and canopy openness by IMI class.

We used regression tree analysis (RTA) to determine major drivers affecting the abundance of oak and hickory small (<50 cm height) and large seedlings (50–140 cm height) in 2006 on all control and TB gridpoints. Each gridpoint was treated independently and the suite of categorical and quantitative predictors included site and treatment, physical variables (canopy openness, IMI, etc.), and vegetation (e.g., abundance of taller competition). The analysis was conducted in SYSTAT (version 11.0) using the default settings. The proportion of reduction in error (PRE) was used as the loss function in terms of a goodness-of-fit statistic; the PRE is basically equivalent to a multiple R^2 statistic.

2.6.2. Potential for oak–hickory regeneration

To better understand competition between oak and hickory and its competitors across the landscape, we developed a rule-based system of classification for each gridpoint based on the abundance and size classes of regeneration. Our objective was to classify the likelihood of the current oak and hickory regeneration to advance into the overstory of the next forest, if the current overstory were removed.

We made several assumptions to simplify the rule-based classification. First, we only evaluated the regeneration layer; we did not incorporate the potential future of stump sprouts from overstory trees (>10 cm) should the remaining overstory be removed (though current sprouts after the TB treatments were accounted for). Second, we treated all oak and hickory species equally (lumped together), and all competition (non-oak and hickory) species equally (lumped together). For example, midstory trees, such as *Carpinus caroliniana* and *Oxydendrum arboreum* were treated the same as species that can attain overstory stature, such as red maple and yellow-poplar. Third, we focused our classification on the advance regeneration layer (stems 50 cm tall to 10 cm dbh), unless total stem densities were below minimum thresholds for each size class (see below). Fourth, the rules were weighted according to the size class of the advance regeneration; e.g., stems in the larger size class (3–10 cm dbh; large saplings) were weighted more than stems 140 cm height to 3 cm dbh (small saplings), which were, in turn, weighted more than the 50–140 cm height class (large seedlings). Fifth, we assumed that, given the capacity of oak and hickory to have greater root:shoot ratios than competitors (Johnson et al., 2002), oak could be classified as ‘‘competitive’’ even if outnumbered and outsized to some degree by competing species.

Each gridpoint was assigned to one of eight competition classes, depending on total density of advance regeneration and seedlings of all species. Class assignments were based on minimum thresholds established from natural breaks in the data.

The advance regeneration classes (classes 1–4, Table 1) were above the thresholds, for all species combined, of one or more of the following criteria: (1) 2500 stems/ha in the large seedling size class; (2) 300 stems/ha in the small sapling size class; (3) 300 stems/ha in the large sapling size class. Classes within the advance regeneration group were assigned based on numbers of seedlings or saplings of oak and hickory larger than 50 cm in height and the competition load from other species. Competition load was defined as high, medium, and low based on the number and sizes of the competing vegetation.

The seedling regeneration classes (classes 5–8, Table 1) were below the thresholds, for all species combined, of all of the same criteria. Classes within the seedling regeneration group were assigned based on numbers of oak and hickory small seedlings (<50 cm in height) present on the plot (Table 1).

In this assessment, we assume the potential for oak regeneration following overstory death or removal to be proportional to the size and quantity of seedlings present, so that class 4, followed by class 8, has the highest probability to

Table 1
Criteria for assigning potential for oak–hickory regeneration

Number of oak + hickory/ha by size			Competition load
Class	>50 cm[a]	<50 cm[b]	
Advanced regeneration classes[c]			
1	<127	na	High
2	127–637	na	High
3	>637	na	Medium
4	>637	na	Low
Seedling regeneration classes[d]			
5	<127	<2500	na
6	<127	2500–5000	na
7	<127	5000–10,000	na
8	<127	>10,000	na

na: not applicable.
[a] Based on number of plants per 78.5 m^2 plot.
[b] Based on number of plants per 8.5 m^2 plot.
[c] Gridpoint's tree population exceeds at least one: (1) 2500 stems/ha of 50–140 cm size; (2) 300 stems/ha of 140 cm height to 2.9 cm dbh or (3) 300 stems/ha of 3.0–9.9 cm dbh.
[d] Gridpoint's tree population does not exceed criteria listed above.

develop into an oak stand should a canopy-opening event occur. We might expect that, across the eight classes, the decreasing order of probability for oak regeneration would be $4 > 8 > 3 > 7 > 2 > 6 > (5, 1)$. We mapped the classification scheme by gridpoint to show variation across the landscape before and after treatments.

3. Results

3.1. Canopy openness

On the ZAL and REMA control units, canopy openness was constant between 2000 and 2001, but decreased by an average of 2.6% (ZAL, decrease from 6.7% to 4.1%) to 3.6% (REMA, decrease from 6.8% to 3.2%) by 2006 (Fig. 1a and b). Some of the consistent decrease in openness from 2000 to 2006 was likely due to variability in decision-making between the analysts when they were thresholding the images (converting from color to black and white [closed/open]) in the GLA program. Though year-to-year variation in open sky can be significant, we would not expect this degree of consistent reduction in canopy openness over 6 years in a mature forest. Therefore, we assume that the same differential in canopy openness estimates (~2–4% decrease) was also likely to have been manifested on the TB sites.

On the ZAL TB unit, canopy openness averaged 7.0% before TB treatment and increased to 12.0% in 2001, the first year after thinning and the first fire (Fig. 1c). Our data suggest a decrease to 9.6% by 2006, but if we factor in the differential of 2–4%, there would be no difference or a slight increase in open sky following the second fire in 2005.

The REMA TB unit averaged 6.1% open sky before treatments and 12.7% after thinning and the first fire (Fig. 1d). In 2006, after the second fire, open sky averaged 13.8% and

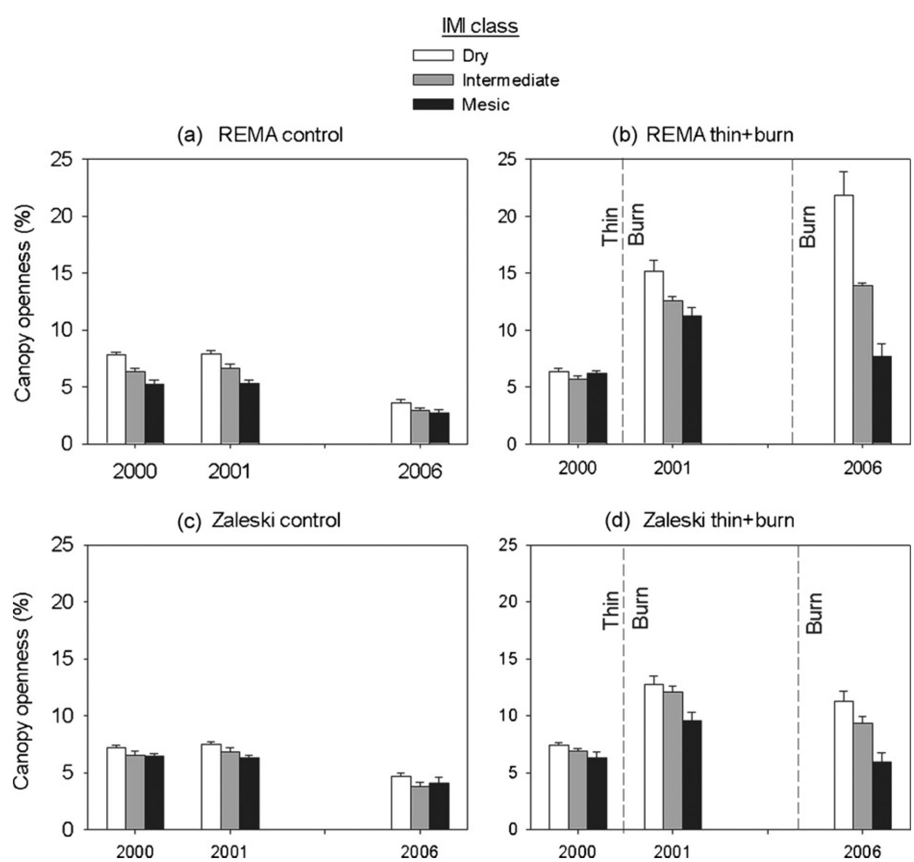

Fig. 1. Estimates of canopy openness for 2000 (before treatment), 2001 (after thinning and first fire), and 2006 (second year after second fire) at ZAL and REMA control and treated sites.

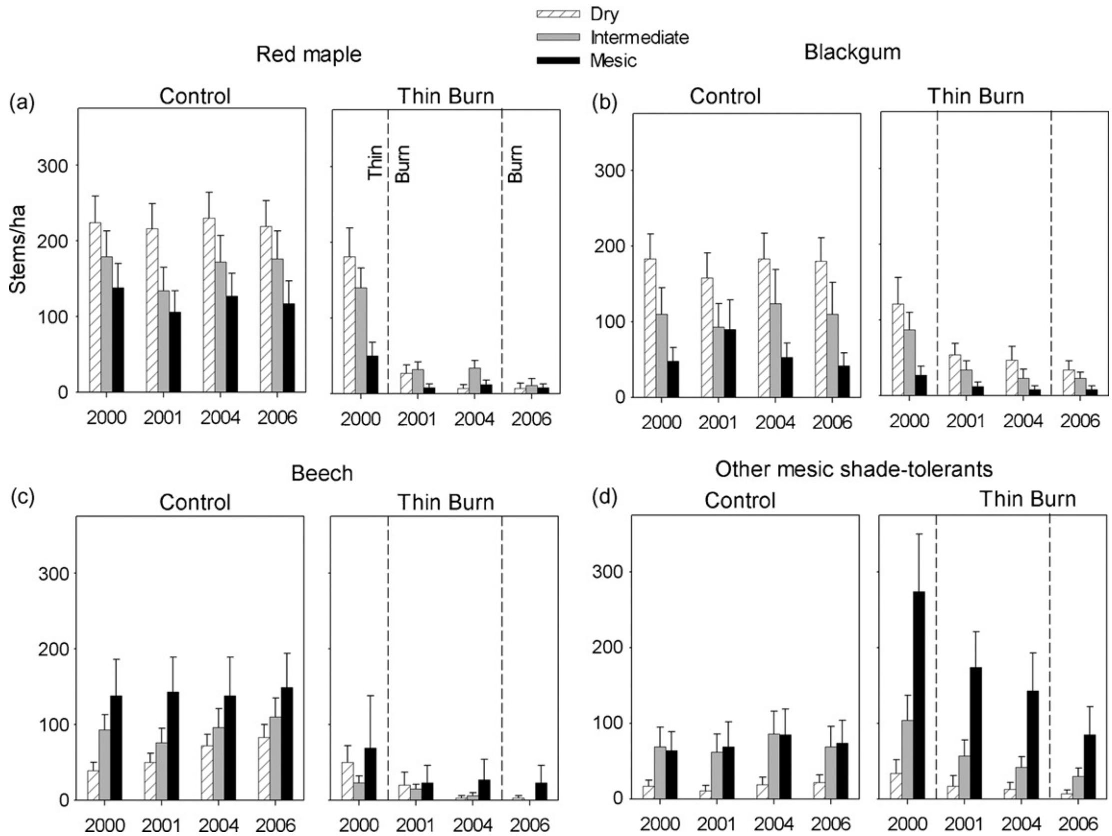

Fig. 2. Changes in large saplings (3.0–10 cm dbh), by IMI class, for several competitors to oak, by treatment and IMI class for 2000, 2001, 2004, and 2006. Thinning occurred in winter 2000–2001, with spring burns in 2001 and 2005. The 'other' category includes the following species: *Acer saccharum*, *Carpinus caroliniana*, *Asimina triloba*, *Cornus florida*, *Cercis canadensis*, and *Oxydendrum arboretum*.

varied considerably among IMI classes, from a mean of 21.8% on dry plots, 13.9% on intermediate plots, and 7.6% on mesic plots. Only one dry plot had <10% open sky in 2006, while more than 70% of mesic plots had <10% open sky.

3.2. Sapling dynamics

For the control plots (all years) and the TB plots in 2000 (before treatment), the most abundant individual species in the large sapling layer (stems 3–10 cm dbh) were red maple and blackgum, which decreased from dry to mesic plots, and American beech, which increased with IMI (Fig. 2). In addition to beech, other shade-tolerant species, including *Acer saccharum*, *Carpinus caroliniana*, and *Asimina triloba*, were quite abundant in some mesic areas, particularly in the REMA TB unit. The REMA TB unit contained a large north-facing slope with higher IMI values than the other three units and thus was somewhat of an outlier.

The TB treatments (REMA and ZAL combined) reduced red maple density sharply between 2000 and 2006, particularly where it had been most abundant on the dry and intermediate plots; mean densities decreased from 181 to 7 stems/ha on dry plots and from 140 to 11 stems/ha on intermediate plots (Fig. 2a). Blackgum density decreased from a mean of 121 to 34 stems/ha on dry plots and from 87 to 23 stems/ha on intermediate plots (Fig. 2b). Beech saplings were less abundant on the two TB units prior to treatment and were largely eliminated from dry and intermediate plots by 2006 (Fig. 2c). The group of other mesic shade-tolerant species decreased from a mean of 274 to 85 saplings/ha on mesic TB plots. On the control units, large sapling densities of all species exhibited relatively little change over the 7-year period, although beech increased from about 50 to 90 saplings/ha on dry plots (Fig. 2c).

3.3. Tree regeneration response to thinning and burning

3.3.1. Oak and hickory

Before treatments on the TB units, mean densities of oak and hickory seedlings (<50 cm) on dry and intermediate plots were more than twice that found on mesic plots (Fig. 3). In 2001, after the initial TB treatments, the numbers of taller oak and hickory seedlings (10–50 and 50–140 cm height) were diminished while the smaller (<10 cm) seedlings increased after resprouting following the initial fire. But this was only a temporary setback. By 2004, seedlings 10–50 cm height were once again more abundant than seedlings <10 cm height, and even the 50–140 cm seedling class numbers were greater than the small seedlings at this time (Fig. 3).

An increase in mean seedling density (both size classes: <10 and 10–50 cm) was evident in 2006, the second year after the second fire and the first year after a large acorn crop (primarily *Quercus prinus*) fell in autumn 2005. Overall, mean densities of

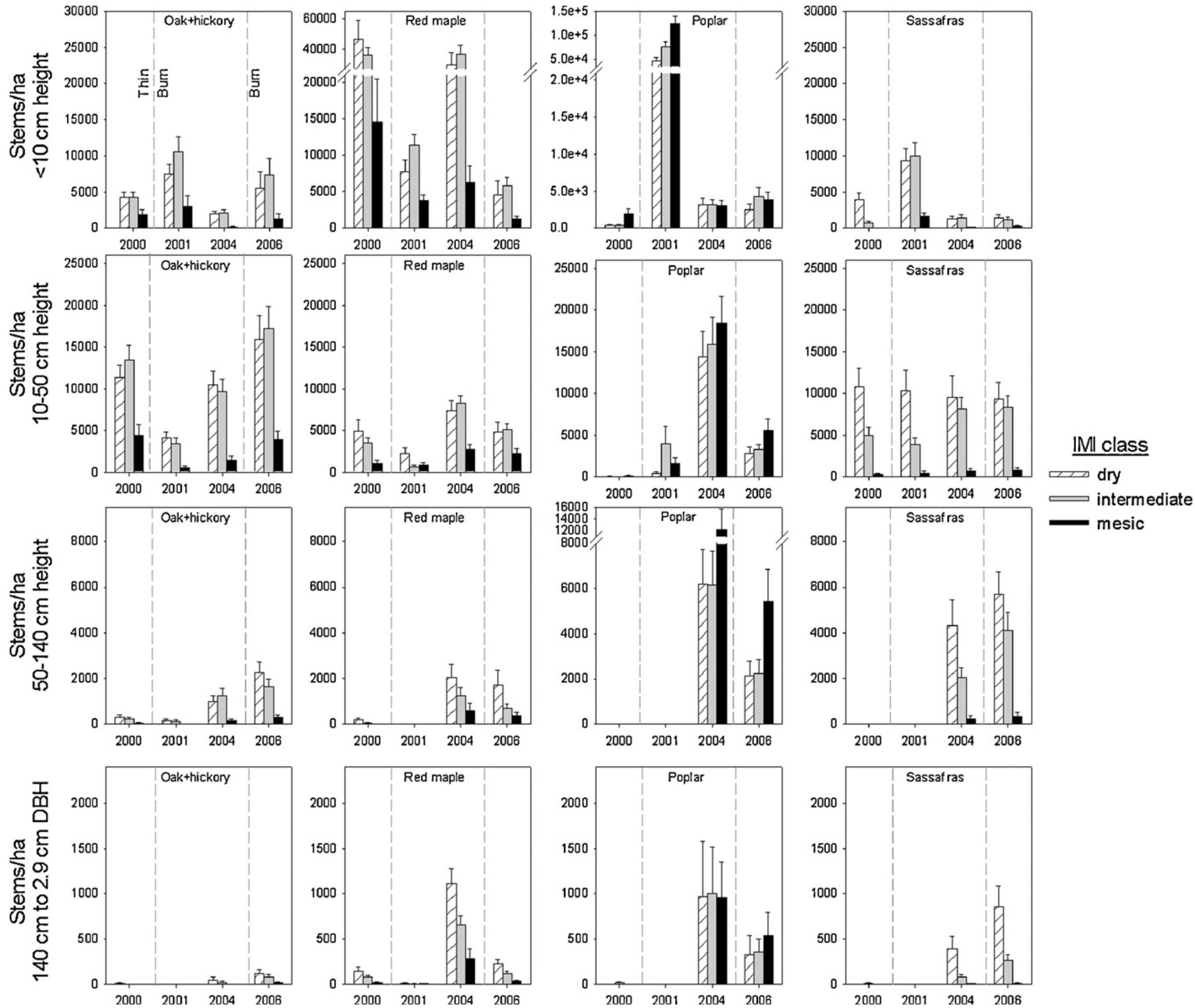

Fig. 3. Changes in seedlings and small saplings, 2000–2006, by IMI class on TB plots for oak and hickory, red maple, yellow-poplar, and sassafras. Thinning occurred in winter 2000–2001, with spring burns in 2001 and 2005.

oak and hickory seedlings (<50 cm) increased 32% from 2000 to 2006.

Prior to treatment, there were very few large seedlings (50–140 cm height) of oak and hickory: densities ranged from 315 ha^{-1} on dry plots to 54 ha^{-1} on mesic plots (Fig. 3). However, large seedlings were much more abundant in 2006, averaging 2240 ha^{-1} and 1640 ha^{-1} on dry and intermediate plots, respectively. On mesic plots, however, large oak and hickory seedling densities remained relatively low by 2006, averaging 290 ha^{-1}. Small saplings (140 cm height to 3 cm dbh) of oak and hickory were nearly absent before treatments and by 2006 their density had increased to an average of 120 and 80 ha^{-1} on dry and intermediate plots, respectively.

Detailed data on individual species of oak (*Quercus alba*, *Q. coccinea*, *Q. prinus*, *Q. rubra*, *Q. velutina*) and *Carya* spp. are presented in online Supplement 1. In general, density shifts by year, IMI, and treatment for individual species are fairly similar to the overall oak and hickory trends shown in Fig. 3.

3.3.2. Red maple (A. rubrum)

Small seedlings (<10 cm) of red maple were reduced dramatically after the 2001 and 2005 fires (Fig. 3). Due to the sprouting of stems (large saplings and small trees) that were topkilled after thinning and burning, there were substantial increases in the density of large seedling (50–140 cm height) and small sapling (140 to 3 cm dbh) stems by 2004. The highest densities were on the dry plots for both large seedlings (mean = 2040 ha^{-1}) and small saplings (1110 ha^{-1}). However, in 2006, after the 2005 fires, the mean density of red maple small saplings had been reduced to <20% of that in 2004.

3.3.3. Yellow-poplar (L. tulipifera)

Prior to treatments, yellow-poplar occurred at low densities in all regeneration size classes (Fig. 3). Abundant seed germination after the 2001 thinning and burning treatments resulted in dramatic increases in the abundance of small (<10 cm) seedlings in 2001. These seedlings became established at high densities across all IMI classes and reached peak densities in mesic plots (mean = 123,000 ha^{-1}). By 2004, the fourth growing season after treatments, larger seedlings and small saplings of yellow-poplar had become abundant in all IMI classes; however, stem densities declined across all of these size classes after the second fire in 2005. The mean density of seedlings 10–50 cm height declined by 70–80% across all IMI classes, from 2004 to 2006. In 2004, large seedlings (50–140 cm height) were abundant on mesic plots (mean density = 12,170 ha^{-1}) and, though reduced by 2006, maintained an average density of 5420 ha^{-1}, nearly 20 times that of oak and hickory large seedlings on mesic plots. Averaged across all dry and intermediate plots in 2006, oak and hickory numbers exceeded yellow-poplar on the two smaller size classes, but yellow-poplar densities exceeded those of oak and hickory in the larger classes; substantially so for the small saplings (Fig. 3).

3.3.4. Sassafras

Sassafras seedlings (<50 cm) were most abundant on dry plots before treatment, averaging 14,800 ha^{-1} (Fig. 3). Large seedlings (50–140 cm height) and small saplings were rare on all IMI classes. Although the abundance of seedlings <50 cm height remained relatively constant throughout the 7-year period, large seedlings had increased substantially by 2004; on dry plots mean densities increased from 17 ha^{-1} in 2000 to 4310 ha^{-1} in 2004 and on intermediate plots the increase was from 11 to 2020 ha^{-1}. Unlike red maple and yellow-poplar, the density of sassafras large seedlings and small saplings continued to increase after the second fire in 2005. On dry plots, by 2006, the mean density of large sassafras seedlings was 2.5 times that of oak and hickory, and small sapling densities were more than seven times that of oak and hickory (Fig. 3).

3.3.5. Other species

Data for eight other species (*Acer saccharum*, *Carpinus caroliniana*, *Corylus americana*, *F. grandifolia*, *Fraxinus* sp., *Hamamelis virginiana*, *N. sylvatica*, and *O. arboretum*) are presented in an online supplement. In general, all of these species had major reductions in the small sapling (>140 cm height to 3 cm dbh) class between 2000 and 2006 due to the fires, but the density of seedlings generally recovered via sprouting. *O. arboretum*, *Fraxinus* spp., *Carpinus caroliniana*, and *N. sylvatica* were the most abundant of these species, both before and after treatments.

3.4. Tree species relative abundance by size class

Prior to treatment, the oaks and hickories dominated the overstory size classes, with 79% of the stems over 20 cm dbh recorded being oaks or hickories (Fig. 4a). In contrast, red maple was the most abundant species in all five size classes between 1.4 m height and 20 cm dbh, up to 43.7% of the stems in the 6–10 cm class. The small saplings (1.4 m height to 3 cm dbh) were dominated by the other species group (*O. arboretum*, *Acer saccharum*, *Carpinus caroliniana*, *Asimina triloba*, and others) and then red maple, blackgum and beech. The small seedling (10–50 cm height) layer was composed of 42.4% oaks and hickories, while the 50–140 cm seedling layer had a mix of species.

When data were collected in 2006, after thinning and two fires, several shifts in relative abundances were apparent among

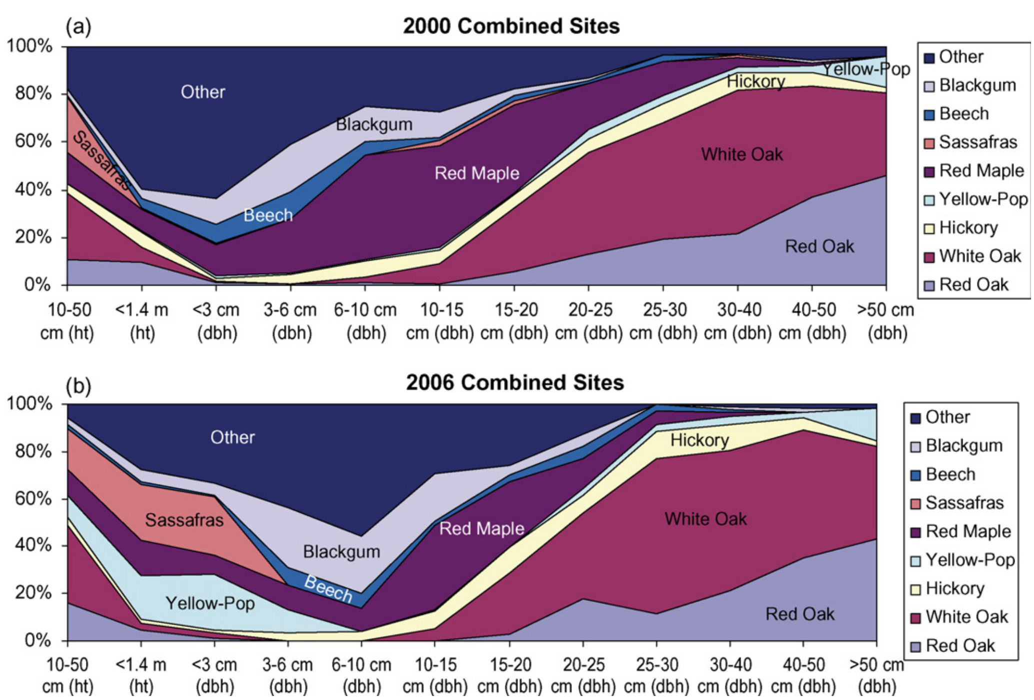

Fig. 4. Relative abundance of species by size class for ZAL and REMA combined in 2000 (before treatment) and 2006 (6 years after thinning and burning).

species groups (Fig. 4b). The species composition of the overstory (>20 cm dbh) was relatively unchanged, although the relative abundance of oaks increased to 84%, while red maple decreased from 8% to 4%. Preferential thinning to retain oak is thus apparent. In the midstory (size classes 10–20 cm dbh) red maple relative abundance decreased from 40% to 31% while blackgum, hickory, and other shade tolerants concomitantly increased. Due to the treatments, the densities were much lower in this size class in 2006 than in 2000.

In the sapling layer (stems 3–10 cm dbh), red maple exhibited the largest change, decreasing from a total of 276 stems/ha in 2000 to 18 stems/ha in 2006. From the much smaller pool of total saplings present in 2006 (905 ha^{-1} in 2000 versus 181 ha^{-1} in 2006), red maple also decreased in relative abundance while yellow-poplar and blackgum increased (Fig. 4).

For the small saplings (140 cm height to 3 cm dbh) and the large seedlings (50–140 cm), all species groups (except beech for the saplings) increased in density between 2000 and 2006. The most dramatic increases were for yellow-poplar and sassafras, which also increased their relative abundance substantially after treatment (Fig. 4). Total numbers of stems in these classes increased nearly 12-fold from 2000 to 2006, to more than 35,000 stems/ha. Among the smaller seedlings (10–50 cm height), the relative abundance of oak and hickory seedlings surpassed 50%, while yellow-poplar increased from <1% to 9.1%, and the other species dropped from about 18% to 6% relative abundance after the treatments.

3.5. Regeneration of oak and hickory related to light and IMI

Plotting the density of 2006 oak and hickory large seedlings (50–140 cm) against canopy openness (for each of the 131 TB gridpoints) reveals a pattern whereby a minimum of about 8.5% canopy openness is required to achieve a density of 1800 ha^{-1} (Fig. 5). Furthermore, 45% of the dry and 32% of the intermediate plots surpassed the 1800 stems/ha threshold, compared to two mesic plots (6%).

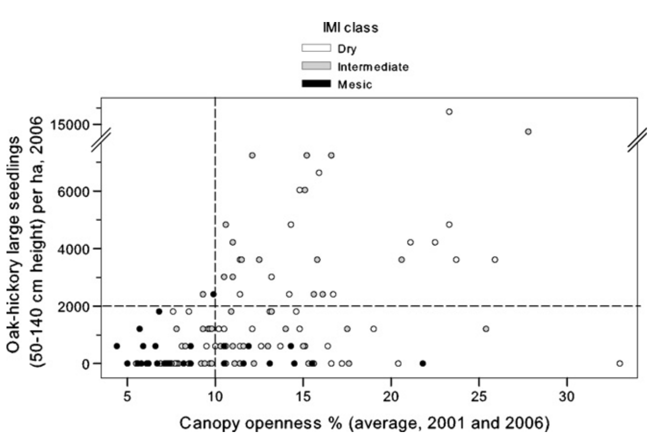

Fig. 5. Scatterplot of the gridpoints (by IMI class) located on both REMA and Zaleski thin and burn units, showing the density of large (50–140 cm height) oak and hickory seedlings 6 years after initial thin and burn treatments. Density is plotted against canopy openness at each gridpoint. The vertical dashed line shows 10% canopy openness and the horizontal line indicates a density of 2000 seedlings/ha.

3.6. Regression tree analysis: factors related to the abundance of oak regeneration

For the abundance of large oak and hickory seedlings (50–140 cm) in 2006, regression tree analysis (RTA) of all plots (control and thin and burn) indicated three significant factors (splits): (1) open sky in 2006 (percent reduction in error [PRE] = 0.19); (2) oak and hickory seedling abundance before treatment (PRE improved to 0.37); (3) the density of competing saplings in 2004 (PRE improved to 0.50) (Fig. 6). Of the four terminal nodes, the largest contained 182 plots with open sky <11.3% and mean oak and hickory density (stems 50–140 cm) of 524 ha^{-1} (S.D. = 960); this group included all 107 control plots and 75 TB plots. Of the remaining 56 TB plots, with open sky >11.3%, there were three nodes with mean densities of 1382 ha^{-1} (n = 38), 2776 ha^{-1} (n = 10), and 7996 ha^{-1} (n = 8). Highest oak and hickory densities thus occurred where open sky exceeded 11.3%, where there were at least 12,500 small (10–50 cm) oak and hickory seedlings prior to treatments in 2000, and where the density of competing saplings (140 to 3 cm dbh) is less than 2800 ha^{-1} (Fig. 6).

In contrast to the RTA of large seedling densities, open sky did not emerge as a key RTA factor in the analysis of small (10–50 cm) oak and hickory seedling abundance in 2006 (Fig. 7). Rather, their abundance was primarily driven by seedling abundance prior to treatment. The three significant factors (splits) for the RTA were (1) oak seedling abundance greater or

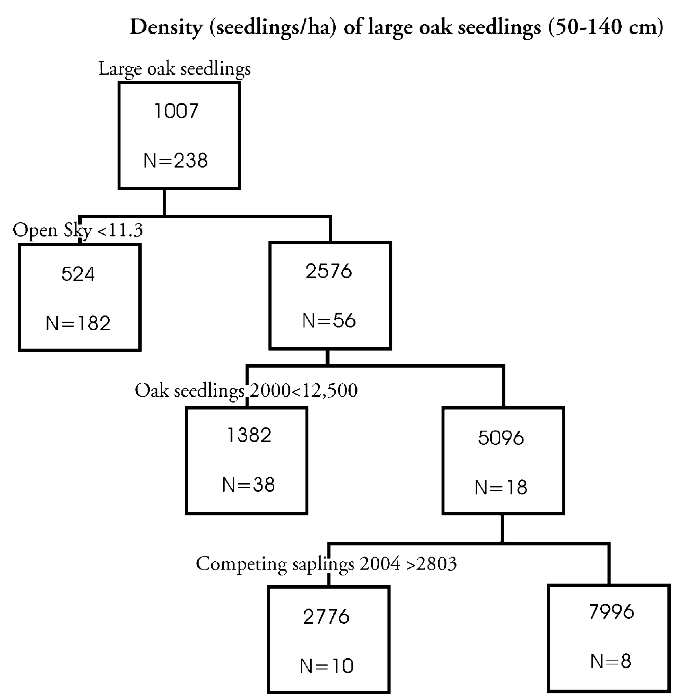

Fig. 6. Regression tree analysis diagram for the abundance of large oak and hickory seedlings (50–140 cm) in 2006 on both control and TB units. The number of seedlings was dependent on open sky, the number of large oak and hickory seedlings in 2000, and the number of competing saplings in 2004.

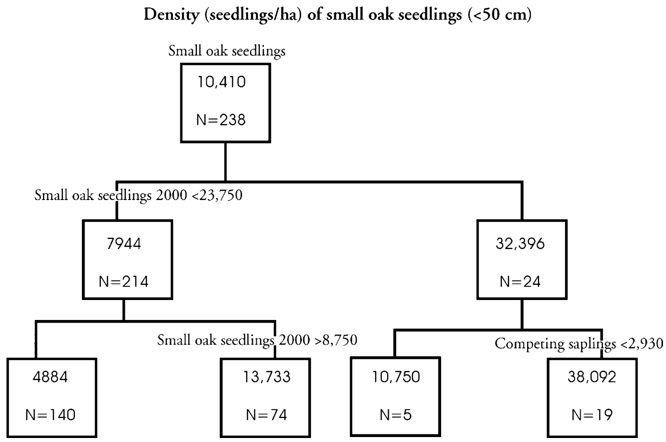

Fig. 7. Regression tree analysis diagram for the abundance of small oak and hickory seedlings (10–50 cm) in 2006 on both control and TB units. The number of small oak and hickory seedlings was dependent on the number of small oak and hickory seedlings in 2000 and the number of competing saplings in 2004.

less than 23,750 ha^{-1} in 2000 (PRE = 0.26); (2) non-oak sapling (140 cm height to 3 cm dbh) density greater or less than 2930 in 2004 (PRE improved to 0.32); (3) oak seedling abundance greater or less than 8750 ha^{-1} (PRE improved to 0.40). Of the four terminal groups, the largest contained 140 plots that had <8750 seedlings/ha in 2000 and in 2006 had a mean abundance of 4884 ha^{-1}; this group contained 65% of control plots and 53% of the TB plots. The second largest group of plots ($n = 74$) had between 8750 and 23,750 seedlings/ha in 2000 and in 2006 the mean density was 13,733 ha^{-1}. The highest oak and hickory seedling (10–50 cm) densities occurred when densities prior to treatment were >23,750 seedlings/ha. This branch was split by the number of competing saplings in 2004: for 19 plots with <2930 competing stems, oak and hickory seedling densities surpassed 38,000 ha^{-1}; this number was nearly quartered if the competing sapling densities exceeded 2930 ha^{-1} (Fig. 7).

3.7. Potential oak–hickory regeneration

To conceptualize the landscape patterns of regeneration, Figs. 8–10 show canopy openness, IMI, and competitive class for the control units in 2006, the ZAL TB unit in 2000 and 2006, and the REMA TB unit in 2000 and 2006, respectively. The circles plotted around each plot center represent the relative proportion of canopy openness. All control plots (Fig. 8) have values for open sky <8.7% regardless of IMI; most plots had less than 5% canopy openness although some plots on the REMA south-facing, low-IMI slopes had values >5%. On the treated units, the effects of the TB treatments are apparent for canopy openness at ZAL (Fig. 9) and REMA (Fig. 10). At REMA, several plots on the southwest-facing slope (low IMI) had very open canopies as a result of the intense fire in 2005, and subsequent overstory mortality.

On the control plots in 2006, oak advance regeneration (>50 cm height) was present and classified as competitive (class 4) on 10% of plots at REMA and 12% of plots at Zaleski (Fig. 8). These plots were located predominantly on dry sites. On these plots, large (50–140 cm) oak and hickory seedling densities averaged 2545 ha^{-1} at REMA and 1145 ha^{-1} at Zaleski.

Prior to treatment (2000), only two plots at ZAL TB contained any large oak seedlings (class 2, Fig. 9a). However, 13 plots (22%) were in class 8, meaning they contained >10,000 ha^{-1} small oak and hickory seedlings (<50 cm). By 2006, thinning and burning had greatly increased the number of

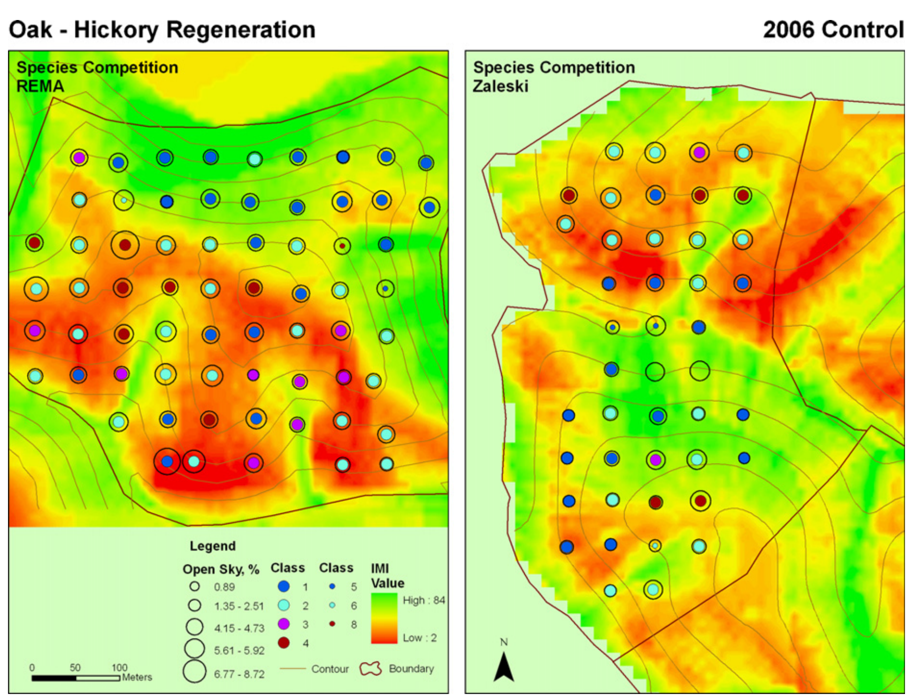

Fig. 8. Competition classes for control plots in 2006, with IMI as background. See Table 1 and text for details on the classes.

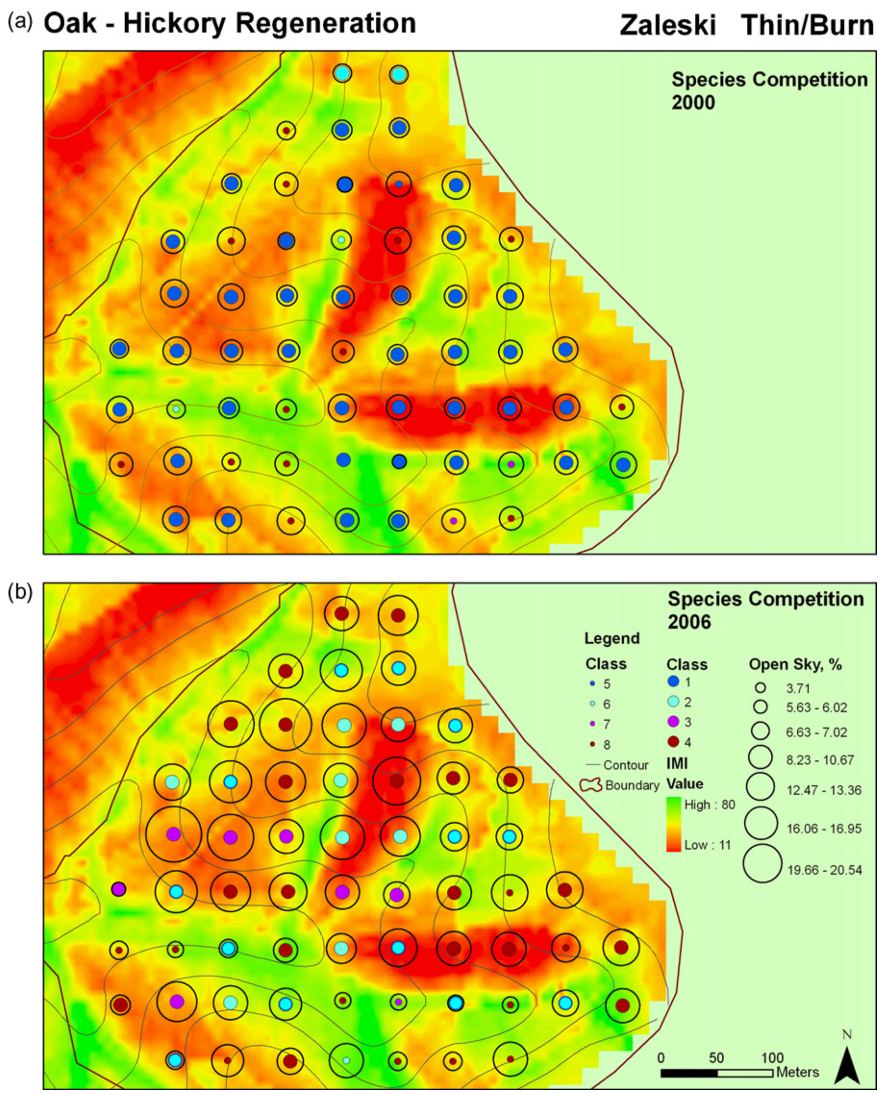

Fig. 9. Competition classes for ZAL TB plots in 2000 and 2006, with IMI as background. See Table 1 and text for details on the classes.

plots containing oak advance regeneration (Fig. 9b). Thirty-five of 60 plots had oak and hickory large seedlings present (classes 2–4), and 20 plots were classified as oak being competitive (class 4). The class 4 plots were distributed throughout the unit but nearly all were on dry or intermediate sites (IMI < 50). If canopy openness was 8.5–19% and IMI was classed as dry or intermediate, we found a 39.4% probability of having oak and hickory classed as competitive. Of those plots matching the light and IMI criteria, if at least 5000 oak and hickory small seedlings (10–50 cm) were present in 2000, the probability for the plot to become competitive for oak increases to 46.4%.

Similar to ZAL, only a few gridpoints on the REMA TB unit contained any large (>50 cm) oak seedlings prior to treatment in 2000 (Fig. 10a). By 2006, overstory mortality resulting from the 2005 fire was evident, as 14 plots had >20% open sky; 12 of which were located on the southwest-facing slope (Fig. 10b). Competition classes in 2006 were clearly different between the southwest-facing slope and the north-facing slope. On the north-facing slope, large oak seedlings were present on 11 of 36 plots but oak was classified as competitive (class 4) on only two plots. On the southwest- and west-facing slope, large oak seedlings were present on 29 of 34 plots and oak was classified as competitive (class 4) on 14 plots. For REMA, when the canopy openness fell between 8.5% and 19% and the IMI was classed as dry or intermediate, 48% of the plots were classified as competitive for oak. If we add the criteria of at least 5000 oak and hickory small seedlings present in 2000, the probability of the plot being competitive rises to 64.7%.

4. Discussion

4.1. *Effects of thinning and burning*

We found that a treatment combining thinning with multiple burns was successful in increasing the density of large oak and hickory seedlings (50–140 cm height). By year seven in this experiment, the mean densities of large oak and hickory seedlings (50–140 cm height) were more than 3× higher on TB (1655 seedlings/ha) than C (507 ha^{-1}) at REMA and more than 5× higher on the ZAL TB unit (1758 ha^{-1}) than on the C unit

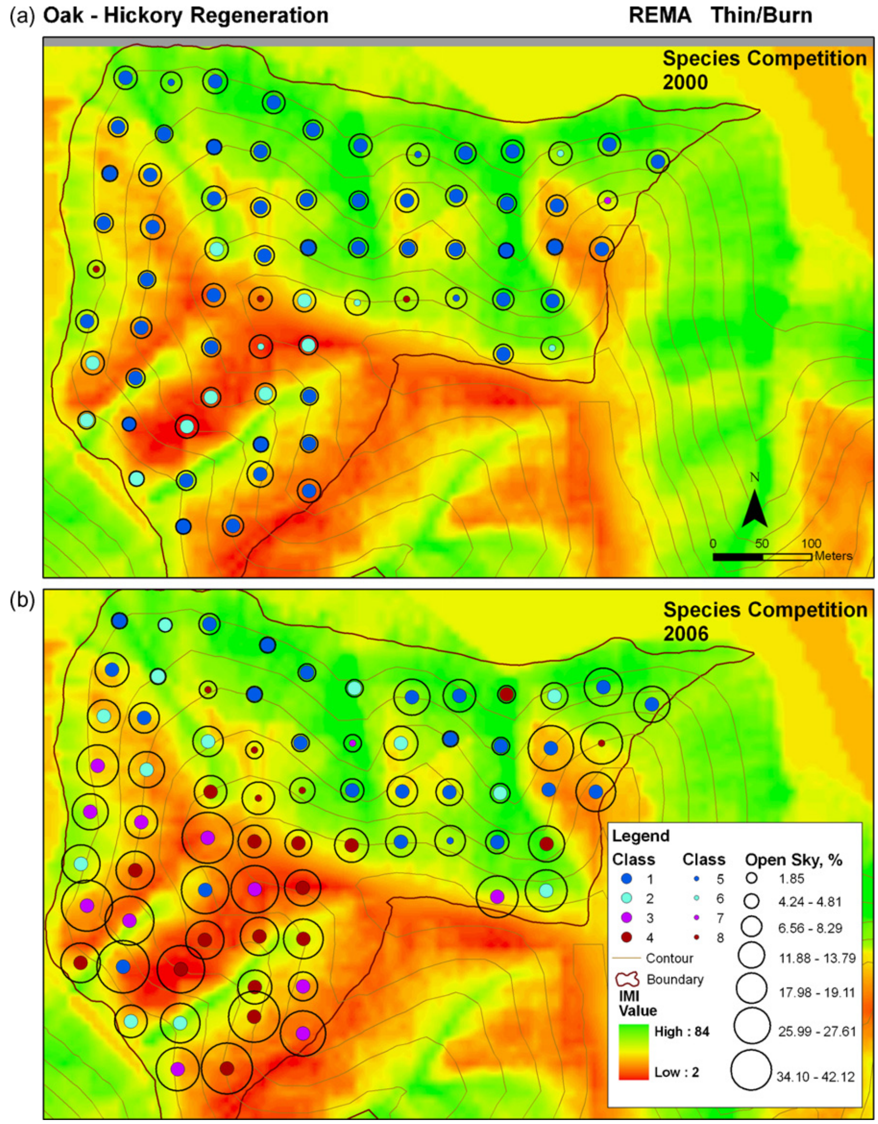

Fig. 10. Competition classes for REMA TB plots in 2000 and 2006, with IMI as background. See Table 1 and text for details on the classes.

(326 ha^{-1}). These results provide some promise for thinning and burning as a management strategy to reverse the declining sustainability of oak that plagues much of the eastern half of the country (Iverson et al., 1997; Abrams, 2003). The second fire appeared to favor oak and hickory regeneration by reducing the dominance of several competitors that had become abundant in the understory following the initial treatments. The second fires also appear to have stimulated oak and hickory seedling growth by maintaining or increasing canopy openness. The higher intensity of the 2005 fires likely was important for reducing competition and increasing canopy openness, although the patches of high overstory mortality that occurred at REMA were not an objective. The 2001 fires, in contrast, were less intense (Iverson et al., 2004c), and perhaps most importantly occurred immediately after the thinning treatment (before competing sprouts and new seedlings established) and thus did not serve to sufficiently reduce understory competition. In fact, in the three growing seasons after the first fire, the competitive status of oak regeneration decreased relative to that of major competitors (e.g., red maple, yellow-poplar) (Albrecht and McCarthy, 2006). Other studies in the region have also shown that repeated low-intensity fires alone were insufficient to stimulate advance oak regeneration (Arthur et al., 1998; Blankenship and Arthur, 2006; Hutchinson et al., 2005). We have verified in this study that thinning combined with multiple, relatively intense fires, timed correctly, can stimulate the development of oak and hickory advance regeneration in our region.

After top-kill, oaks, hickories, and competitors have the capacity to sprout from dormant buds located in the root-collar. However, because of their high root:shoot ratio and often the lower position (more protected) of dormant buds, oaks and hickories are considered to be better able to continue to sprout after repeated top-kills and also more resistant to dormant bud damage during high intensity fires (Van Lear and Watt, 1993; Brose and Van Lear, 1998). A single low-intensity fire, however, provides favorable conditions for rapid growth for light-seeded species (e.g., red maple), seed-banking species (e.g., yellow-poplar), and sprouters (e.g., red maple, blackgum, sassafras, sourwood). To favor oak and hickory regeneration, multiple fires will likely be needed in many areas to reduce the first wave of resprouting competitors.

There was considerable variation in the oak and hickory density across the landscape, both before and after treatment. The differential success for oak regeneration on drier sites has been known for a long time (e.g., Carvell and Tryon, 1961; Johnson, 1993), but the GIS-derived IMI provides an easily-produced gradient metric that can be mapped and linked to oak regeneration suitability and prediction (Iverson et al., 1997, 2004a). The IMI effect was most apparent on the REMA TB treatment (Fig. 9). The observed increases in oak advance regeneration occurred almost exclusively on the dry or intermediate IMI plots located across the southwest-facing slope; these dry and intermediate IMI plots also exhibited much greater canopy openness than the mesic plots on the north-facing slope, a result of higher intensity fires. These results support the possibility of promoting oak and hickory regeneration on the dry and intermediate portions of the landscape. However, these treatments will likely not be effective, at least in the short-term, for developing oak and hickory advance regeneration on mesic landscape positions.

Many studies have been conducted using fire, thinning, or both to promote oak regeneration, with varying degrees of success. Previously mentioned was our study (Hutchinson et al., 2005) which found that multiple fires without thinning did not sufficiently stimulate oak regeneration. However, Dey and Hartman (2005) applied multiple fires to younger dry oak forests in the Missouri Ozarks and found that oak and hickory were favored relative to their competitors. Franklin et al. (2003) reported that low intensity fire and shelterwood cutting in Kentucky did not stimulate oak regeneration, and suggested that ‘more severe disturbance techniques’ are likely needed for sustainable oak forest management in the central hardwoods region. Kruger and Reich (1997a,b) found that a single prescribed fire applied to small openings in young, mesic oak stands in Wisconsin favored red oak regeneration over competitors. Brose and Van Lear (1998) showed that a combination of shelterwood harvest with a single fire (particularly effective were spring growing-season fires) favored oak regeneration over red maple and yellow-poplar in the Virginia Piedmont. Each of these studies varies in forest age and structure, land-use history, site quality, treatments, and results; however, all provide insights to build on in order to address some of the difficulties associated with oak regeneration.

4.2. Oak competitiveness

Our metric of oak competitiveness follows a long line of research showing that the ultimate success of oak regeneration depends greatly on the number, size, and spatial distribution of the oak advance reproduction present when the canopy is removed. The advance regeneration present is largely a function of site quality (IMI, fertility), intensity of competition, and the structure and composition of the mid- and overstory, which determine canopy openness (Carvell and Tryon, 1961; Loftis, 1990; Johnson, 1993). An inspection of the maps of competition class, IMI, and canopy openness (Figs. 9 and 10) shows the interconnectedness among these factors. Those places with drier IMI values tended to have greater canopy openness (largely due to higher intensity fires), which in turn supported the development of competitive oak and hickory advance regeneration. Adequate light availability has been shown to be critical for oak and hickory regeneration success. However, high light levels can also stimulate shade-intolerant species such as yellow-poplar (Loftis and McGee, 1993; Hodges and Gardiner, 1993). In our study, the development of significant numbers of taller oak regeneration (>1800 stems/ha and >50 cm height) occurred almost exclusively on plots with 8.5–19% canopy openness (post-treatment average for 2001 and 2006). This canopy openness range is similar to that reported in studies that showed an increase in oak advance regeneration when stand basal area was reduced mechanically (e.g., Loftis, 1993).

A simple model incorporating these trends shows that, at any point on the landscape, if canopy openness can be increased to 8.5–19%, the IMI value is dry or intermediate (IMI < 50), and sufficient seedlings (10–50 cm) were present prior to treatment (>5000 ha^{-1}), one can expect a 54% probability that the oak and hickory component would become competitive according to our rating scheme for the combined sites. This probability was higher on REMA (65%) versus ZAL (46%) presumably because of the higher intensity fires and greater canopy openness on the dry and intermediate locations at REMA. If we included class 3 (similar number of large oak seedlings present but greater competition load, Table 1) along with class 4, the probability rises to 67%. This simple model allows a quick, practical method in targeting fire and thinning operations for maximum benefit in regenerating oak communities: focus on sites of dry or intermediate IMI (generally includes ridges and upper slopes of all aspects and all south-facing slopes) with at least one oak and hickory seedling every 2 m^2, thin the stand to increase canopy openness, and then burning at least twice over the ensuing 5–10 years. However, our study suggests that burning immediately after thinning provides only limited control of competition, which has not yet developed in the understory.

Small seedlings (<50 cm) of oak and hickory also increased substantially between 2004 and 2006, much more so at the ZAL TB than at REMA TB. The difference between sites can be explained by two differences: a mast year for chestnut oak (*Q. prinus*) in 2005 and the variation in fire severity between the two sites. ZAL has a higher proportion of chestnut oak in the canopy (most of the ‘white’ oak component, Fig. 4), whereas REMA has a relatively larger white oak (*Q. alba*) and red oak component. Chestnut oak’s large mast in autumn 2005, after the spring 2005 fire, therefore resulted in greater seedling establishment in 2006 at ZAL TB. At REMA, the high intensity 2005 fires on the dry sites killed substantial patches of overstory oaks, thus reducing seed sources; the open canopy also stimulated extensive competition from *Rubus* spp. and other species. In contrast, the burn at ZAL was generally of moderate intensity throughout the unit and killed few overstory oaks. These oaks, dominated by chestnut oak, then produced a large crop of acorns and new seedlings, which may also have benefited from an improved seedbed for germination and establishment.

4.3. Competitor species

Many of the species competing with oaks and hickories were also greatly affected by the treatments over time. The species with the largest dynamics over time were red maple, yellow-poplar, and sassafras, though the 'other species' group was abundant in certain locations (especially mesic sites). As is apparent by now, the competition of non-oak species, along with the site conditions (e.g., IMI, light) and the number and size of oak and hickory plants in place prior to treatment determines whether oak and hickory regeneration will be successful.

The huge influxes of small seedlings on the TB-treated sites are primarily new yellow-poplar seedlings that appeared after the initial TB treatment. Small red maple seedlings were also abundant across the landscape but were reduced by fire treatments. The highest numbers of seedlings at any time were found on the mesic sites in 2001, just after the initial treatment, when the densities of non-oaks (predominantly yellow-poplar) exceeded 120,000 (REMA) and 150,000 (ZAL) seedlings/ha (equivalent to 12–15 seedlings/m^2 across the entire landscape). However, these densities were not sustained; after the second burn in 2005, the density of small non-oak seedlings was actually lower on the TB units than on the controls.

The density of non-oak seedlings in the 10–50 cm size class peaked in 2004. This probably indicates that growth (and self-thinning) ensued following the 2001 flush of germinants, and that many of the germinants had grown into the 10–50 cm class by 2004. The fires of 2005 produced heavy mortality so that the densities in 2006 were again lower. The second fire was critically important in this regard, altering the successional progression apparent from the earlier work by Albrecht and McCarthy (2006).

The advance regeneration (large seedling and small saplings) of non-oak species was most abundant in 2004, likely a result of a post-treatment stimulation of germinants (e.g., yellow-poplar) and sprouts (e.g., red maple) resulting from the initial thinning and burning treatment. For example, red maple had as many as 30 stems sprouting from one cut 10–15 cm tree. These stems were reduced by the 2005 burn, especially in the dry and intermediate sites. However, the density of sassafras advance regeneration, which was abundant on dry sites, actually increased after the second burns.

Overall, we found that there was, and continues to be even after our treatments, substantial competition for oak regeneration across much of the landscape. This competition likely reduced the size and number of oaks and hickories developing into the advance regeneration layer. In drier landscape positions, competition was greatest from red maple, sassafras, yellow-poplar, and blackgum. Additional competition from dense thickets of shrubs such as *Smilax* spp. and *Rubus* spp., was also prevalent across the landscape.

5. Conclusion

Despite receiving much attention in the last several decades, regenerating oak continues to be difficult throughout the eastern United States. The multitude of natural and human values created by oak-dominated communities underscores the need to develop better tools to sustain oak forests. Our study of thinning and burning on relatively large (>20 ha) treatment units shows some promise and also some of the problems that managers face (management scale). Though thinning and burning increased the density of oak advance regeneration (large seedlings 50–140 cm), there also was ample competition from species that had different strategies in dealing with the new conditions brought about by the thinning and burning. We found that there was a large spatial variation in oak regeneration across these large sites because topography, fire intensity, and canopy openness were also highly variable. Our simple model for this region suggests that if a mature forest on a dry or intermediate site with at least 5000 oak and hickory seedlings/ha is thinned and burned to reduce competition and sustain 8.5–19% canopy openness, there is a 50% chance (or 50% of the treated area matching these criteria) of success in oak and hickory becoming competitive for a position in the next forest. We thus are encouraged by the results of this study and intend to continue to monitor the structure and composition of tree regeneration on these sites.

Acknowledgements

The authors are indebted to a host of field workers that helped make this possible, including Robert Ford, Aaron Iverson, Rebecca Wells, Brian McCombs, Justin Prindle, Jeff Mathews, David Hosack, Levi Miller, William Borovicka, Kristy Tucker, and Brad Tucker. Rebecca Wells also analyzed the hemispherical photographs for 2000 and 2001. Thanks also to Daniel Yaussy for oversight as manager for the FFS study in Ohio, Mary Boda as project coordinator, and Michael Bowden and the Ohio Division of Forestry for their lead in conducting the burns and thinning. We thank Matthew Albrecht, Ralph Boerner, John Stanovich, and Lars Brudvig for reviews and Susan Wright for technical edits, which greatly improved the manuscript. This is contribution number 150 of the National Fire and Fire Surrogate Research Project. Although the authors received no direct funding from the U.S. Joint Fire Science Program (JFSP), this research could not have been accomplished without JFSP support of existing Fire and Fire Surrogate project sites. This research was also supported in part by the National Fire Plan through the Ohio Hills Fire Behavior and Effects project administered by USFS Project NRS-4151.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.foreco.2007.09.088.

References

Abrams, M.C., 2003. Where has all the white oak gone? BioScience 53, 927–939.

Albrecht, M.A., McCarthy, B.C., 2006. Effects of prescribed fire and thinning on tree recruitment patterns in central hardwood forests. For. Ecol. Manage. 226, 88–103.

Arthur, M.A., Paratley, R.D., Blankenship, B.A., 1998. Single and repeated fires affect survival and regeneration of woody and herbaceous species in an oak-pine forest. J. Torrey Botan. Soc. 125 (3), 225–236.

Beatley, J.C., Bartley, F., 1959. The primeval forests of a periglacial area in the Allegheny Plateau. Bull. Ohio Biolog. Survey 1, 25–166.

Beck, D.E., 1990. *Liriodendron tulipifera* L. Yellow-poplar. In: Burns, R.M., Honkala, B.H. (tech coords.), Silvics of North America: 2. Hardwoods. U.S.D.A., Agricul. Handb. 654, pp. 406–416.

Blankenship, B.A., Arthur, M.A., 2006. Stand structure over 9 years in burned and fire-excluded oak stands on the Cumberland Plateau, Kentucky. For. Ecol. Manage. 225, 134–145.

Boerner, R.E.J., 2006. Unraveling the Gordian Knot: interactions among vegetation, topography, and soil properties in the central and southern Appalachians. J. Torrey Botan. Soc. 133, 321–361.

Boerner, R.E.J., Morris, S.J., Sutherland, E.K., Hutchinson, T.F., 2000. Spatial variability in soil nitrogen dynamics after prescribed burning in Ohio mixed-oak forests. Landsc. Ecol. 15, 425–439.

Brose, P.H., Van Lear, D.H., 1998. Responses of hardwood advance regeneration to seasonal prescribed fires in oak-dominated shelterwood stands. Can. J. For. Res. 28, 331–339.

Brose, P., Van Lear, D., Cooper, R., 1999. Using shelterwood harvests and prescribed fire to regenerate oak stands on productive upland sites. For. Ecol. Manage. 113, 125–141.

Brose, P., Schuler, T., Van Lear, D., Berst, J., 2001. Bringing fire back. The changing regimes of the Appalachian mixed-oak forests. J. For. 99, 30–35.

Carvell, K.L., Tryon, E.H., 1961. The effect of environmental factors on the abundance of oak regeneration beneath mature oak stands. For. Sci. 7, 98–105.

Chen, J., Saunders, S.C., Crow, T.R., Naiman, R.J., Brosofske, K.D., Mroz, G.D., Brookshire, B.L., Franklin, J.F., 1999. Microclimate in forest ecosystem and landscape ecology. BioScience 49, 288–297.

Dennis, D.F., Birch, T.W., 1981. Forest statistics for Ohio-1979. U.S.D.A. Forest Service, Northeastern Research Station, Resource Bulletin NE-68.

Dettmers, R., Bart, J., 1999. A GIS modeling method applied to predicting forest songbird habitat. Ecol. Appl. 9, 152–163.

Dey, D.C., Hartman, G., 2005. Returning fire to Ozark Highland forest ecosystems: effects on advance regeneration. For. Ecol. Manage. 217, 37–53.

Dickinson, M.B. (Ed.), 2006. Fire in eastern oak forests: delivering science to land managers, Proceedings of a Conference; U.S.D.A. Forest Service, Northern Research Station Gen. Tech. Rep. NRS-P-1.

Dyer, J.M., 2001. Using witness trees to assess forest change in southeastern Ohio. Can. J. For. Res. 31, 1708–1718.

Franklin, S.B., Robertson, P.A., Fralish, J.S., 2003. Prescribed burning effects on upland *Quercus* forest structure and function. For. Ecol. Manage. 184, 315–335.

Frazer, G.W., Canham, C.D., Lertzman, K.P., 1999. Gap Light Analyzer (GLA), Version 2.0: Imaging software to extract canopy structure and gap light transmission indices from true-colour fisheye photographs, users manual and program documentation. Simon Fraser University and the Institute of Ecosystem Studies, Burnaby, British Columbia and Millbrook, NY.

Griffith, D.M., DiGiovanni, D.M., Witzel, T.L., Wharton, E.H., 1993. Forest statistics for Ohio, 1991. U.S.D.A. Forest Service, Northeastern Forest Experiment Station, Resource Bulletin NE-128.

Hilt, D.E., 1985. Species composition of young central hardwood stands that develop after clearcutting. In: Dawson, J.O., Majerus, K.A. (Eds.), Proceedings of the Fifth Central Hardwood Forest Conference. University of Illinois, Department of Forestry, pp. 11–14.

Hodges, J., Gardiner, E., 1993. Ecology and physiology of oak regeneration. In: Loftis, D.L., McGee, C.E. (Eds.), Oak regeneration: serious problems, practical recommendations. U.S.D.A. Forest Service, Southeastern Forest Experiment Station. General Technical Report SE-84, pp. 54–65.

Hutchinson, T.F., Boerner, R.E.J., Iverson, L.R., Sutherland, S., 1999. Landscape patterns of understory composition and richness across a moisture and nitrogen mineralization gradient in Ohio (U.S.A.) Quercus forests. Plant Ecol. 144, 179–189.

Hutchinson, T.F., Sutherland, E.K., Yaussy, D.A., 2005. Effects of repeated prescribed fires on the structure, composition, and regeneration of mixed-oak forests in Ohio. For. Ecol. Manage. 218, 210–228.

Iverson, L.R., Dale, M.E., Scott, C.T., Prasad, A., 1997. A GIS-derived integrated moisture index to predict forest composition and productivity in Ohio forests. Landsc. Ecol. 12, 331–348.

Iverson, L.R., Oliver, R.L., Tucker, D.P., Risser, P.G., Burnett, C.D., Rayburn, R.G., 1989. Forest resources of Illinois: an atlas and analysis of spatial and temporal trends. Ill. Nat. Hist. Survey Spec. Publ. 11, Champaign, IL.

Iverson, L.R., Prasad, A.M., Hutchinson, T.F., Rebbeck, J., Yaussy, D.A., 2004a. Fire and thinning in an Ohio oak forest: grid-point analysis of fire behavior, environmental conditions, and tree regeneration across a topographic moisture gradient. In: Spetich, M. (Ed.), Upland Oak Ecology Symposium: History, Current Conditions, and Sustainability. U.S.D.A. Forest Service, Southern Research Station, General Technical Report SRS-73, pp. 190–197.

Iverson, L.R., Prasad, A.M., Rebbeck, J., 2004b. A comparison of the integrated moisture index and the topographic wetness index as related to two years of soil moisture monitoring in Zaleski State Forest, Ohio. In: Yaussy, D.A., Hix, D.M., Goebel, P.C., Long, R.P. (Eds.), Proceedings of the 14th Central Hardwoods Conference. U.S. Forest Service, Northeastern Research Station General Technical Report NE-316, pp. 515–517.

Iverson, L.R., Scott, C.T., Dale, M., Prasad, A.M.G., 1996. Development of an integrated moisture index for predicting species composition. In: Kohl, M., Gertner, G.Z. (Eds.), Caring for the forest: research in a changing world. Statistics, mathematics, and computers. Proceedings of the meeting of IUFRO S.4.11-00. Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf, Switzerland, pp. 101–116.

Iverson, L.R., Yaussy, D.A., Rebbeck, J., Hutchinson, T.L., Long, R., Prasad, A.M., 2004c. A comparison of thermocouples and paints to monitor the spatial and temporal distribution of fire behavior from prescribed fires. Int. J. Wildland Fire 13, 311–322.

Johnson, P.S., 1993. Sources of oak reproduction. In: Loftis, D.L., McGee, C.E. (Eds.), Oak regeneration: serious problems, practical recommendations. U.S.D.A. Forest Service, Southeastern Forest Experiment Station, General Technical Report SE-84, pp. 202–210.

Johnson, P.S., Shifley, S.R., Rogers, R., 2002. The Ecology and Silviculture of Oaks. CABI Publishing, New York, NY.

Kang, S., Kim, S., Lee, D., 2000. Predicting spatial and temporal patterns of soil temperature based on topography, surface cover and air temperature. For. Ecol. Manage. 136 (1/3), 173–184.

Kingsley, N.P., Mayer, C.E., 1970. The timber resources of Ohio. U.S.D.A. Forest Service, Northeastern Forest Experiment Station, Resource Bulletin NE-19.

Kruger, E.L., Reich, P.B., 1997a. Responses of hardwood regeneration to fire in mesic forest openings. I. Post-fire community dynamics. Can. J. For. Res. 27, 1822–1831.

Kruger, E.L., Reich, P.B., 1997b. Responses of hardwood regeneration to fire in mesic forest openings. III. Whole-plant growth, biomass distributions, and nitrogen and carbohydrate relations. Can. J. For. Res. 27, 1841–1850.

Leete, B.E., 1938. Forest fires in Ohio 1923 to 1935. Ohio Agricul. Exper. Sta., Bulletin 598.

Loftis, D.L., 1990. A shelterwood method for regenerating red oak in the Southern Appalachians. For. Sci. 36, 917–929.

Loftis, D.L., 1993. Regenerating northern red oak on high-quality sites in the Southern Appalachians. In: Loftis, D.L., McGee, C.E. (Eds.), Oak regeneration: serious problems, practical recommendations. U.S.D.A. Forest Service, Southeastern Forest Experiment Station. General Technical Report SE-84, pp. 202–210.

Loftis, D.L., McGee, C.E. (Eds.), 1993. Oak regeneration: serious problems, practical recommendations. U.S.D.A. Forest Service, Southeastern Forest Experiment Station. General Technical Report SE-84.

Marquis, D., 1990. *Prunus serotina* Ehrh. Black cherry. In: Burns, R.M., Honkala, B.H. (tech coords.) Silvics of North America: 2. Hardwoods. U.S. Department of Agriculture, Agric. Handbk 654, pp. 594–602.

McEwan, R.W., Long, R.P., Ford, R.D., Hutchinson, T.F., McCarthy, B.C., 2007. Temporal and spatial patterns of fire occurrence during the establishment of mixed-oak forests in eastern North America. J. Veg. Sci. 18, 655–664.

McShea, W.J., Healy, W.H., 2002. Oak forest ecosystems. In: Ecology and Management for Wildlife, The Johns Hopkins University Press, Baltimore.

McWilliams, W.H., Alerich, C.A., Devlin, D.A., Lister, A.J., Lister, T.W., Sterner, S.L., Westfall, J.A., 2004. Annual inventory report for Pennsylvania's forests: results from the first three years. U.S.D.A. Forest Service, Northeastern Research Station, Resource Bulletin NE-159.

Nowacki, G.J., Abrams, M.D., 1992. Community, edaphic, and historical analysis of mixed oak forests of the ridge and valley province in central Pennsylvania. Can. J. For. Res. 22, 790–800.

Rebbeck, J., Long, R.P., Yaussy, D.A., 2004. Survival of hardwood seedlings and saplings one year following a prescribed fire and overstory thinning in southeastern Ohio. In: Yaussy, D.A., Hix, D.M., Long, R.P., Goebel, P.C. (Eds.), Proceedings of the 14th Central Hardwood Forest Conference. U.S.D.A. Forest Service, Northeastern Research Station, General Technical Report NE-316, p. 210.

Southern Appalachian Man and the Biosphere (SAMAB), 1996. The Southern Appalachian Terrestrial Technical Report. Report 5 of 5. U.S.D.A. Forest Service, Southern Region.

Spetich, M.A. (Ed.), 2004. Upland oak ecology. Symposium: history, current conditions, and sustainability. U.S.D.A. Forest Service, Southern Research Station, General Technical Report SRS-73.

Sutherland, E.K., 1997. History of fire in a southern Ohio second-growth mixed-oak forest. In: Pallardy, S.G., Cecich, R.A., Garrett, H.E., Johnson, P.S. (Eds.), Proceedings of the 11th Central Hardwood Forest Conference. U.S.D.A. Forest Service, North Central Forest Experiment Station, General Technical Report NC-188, pp. 172–183.

Sutherland, E.K., Hutchinson, T.F. (Eds.), 2003. Characteristics of mixed-oak forests in Ohio. U.S.D.A. Forest Service, Northeastern Research Station, General Technical Report NE-299.

Van Lear, D.H., Watt, J.M., 1993. The role of fire in oak regeneration. In: Loftis, D.L., McGee, C.E. (Eds.), Oak regeneration: serious problems, practical recommendations. U.S.D.A. Forest Service, Southeastern Forest Experiment Station, General Technical Report SE-84, pp. 66–78.

Youngblood, A., Metlen, K.L., Knapp, E.E., Outcalt, K.W., Stephens, S.L., Waldrop, T.A., Yaussy, D., 2005. Implementation of the fire and fire surrogate study—a national research effort to evaluate the consequences of fuel reduction treatments. In: Peterson, C.E., Maguire, D.A. (Eds.), Balancing ecosystem values: innovative experiments for sustainable forestry: proceedings of a conference. U.S.D.A. Forest Service, Pacific Northwest Research Station, General Technical Report PNW-635, pp. 315–321.

Zheng, D.L., Chen, J.Q., Song, B., Xu, M., Sneed, P., Jensen, R., 2000. Effects of silvicultural treatments on summer forest microclimate in southeastern Missouri Ozarks. Clim. Res. 15, 45–59.