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Stand structure over 9 years in burned and fire-excluded oak stands on the Cumberland Plateau, Kentucky

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Abstract

Upland oak-dominated forests in the central Appalachian region are being managed increasingly with prescribed fire, ostensibly to reduce midstory stem density of fire-sensitive species and to promote oak regeneration, creating the need to document the effectiveness of fire alone for accomplishing these objectives. On three ridges in the Daniel Boone National Forest, Kentucky, changes in stand structure and tree regeneration were examined from 1995 to 2003 in oak-dominated stands where fire-sensitive red maple (*Acer rubrum* L.) and eastern white pine (*Pinus strobus* L.) were gaining dominance. Fire-excluded and burn treatments were applied to the three ridges, such that each ridge contained three units receiving one of the following treatments: fire-excluded, burned 2×, or burned 3×.

Burning reduced midstory (2–10 cm DBH) stem density by 91% and midstory basal area by 86%, whereas on fire-excluded units, midstory stem density decreased 24% and basal area 28%. Burning reduced overstory (≥10 cm DBH) stem density 30% but did not significantly affect overstory basal area. Overstory stem density on fire-excluded units did not change but overstory basal area decreased 10%.

Repeated burning reduced midstory red maple stem density 94%, compared to fire-excluded units, which experienced a 39% decrease in midstory red maple stem density and an 85% increase in overstory red maple stem density and basal area. Burning reduced midstory oak (*Quercus* spp.) stem density 82%, while on fire-excluded units, a decline in midstory oak stem density was not significant. Overstory oak stem density decreased 25% on both fire-excluded and burned units.

Damaged and dead stems on burned units responded by sprouting vigorously, with red maple being the most prolific. The number of basal sprouts/stem increased with each additional fire and the basal sprout density (sprouts/ha) was highest after the third fire. Burning also affected tree regeneration by eliminating eastern white pine stems in the sapling layer (≥50 cm height and <2 cm DBH). Red maple stem density in the sapling-layer was highest on the 3×-burned units primarily due to basal sprouting. Seedling-layer (<50 cm height) oak and flowering dogwood stems were also highest on units burned 3×.

Multiple prescribed fires successfully reduced midstory densities of fire-sensitive species such as red maple, but also negatively affected oaks. Additional silvicultural methods to augment prescribed fire, or changing the timing and/or intensity of burning may be necessary for restoring oak-dominated stands.

Keywords: Eastern white pine; Flowering dogwood; Oak regeneration; Prescribed burning; Red maple; Sprouting

1. Introduction

Fire has been considered an important factor in the establishment and maintenance of oak-dominated forests (Lorimer, 1980; Abrams, 1992; Abrams and Nowacki, 1992; Mikan et al., 1994), and in the southern Appalachian region, pollen and charcoal data indicate a close relationship between fire and oak dominance (Delcourt and Delcourt, 1998). More and more, oak stands appear to be succeeding to shade-tolerant species such as red maple (*Acer rubrum* L.) and sugar maple (*A. saccharum* Marsh.) (Lorimer, 1984; Abrams, 1998; Stephenson and Fortney, 1998). This changing composition in eastern deciduous forests has been linked to fire suppression, but other influences were and are important as well, such as loss of American chestnut (*Castanea dentata* [*Marshall*] *Borkh.*) (Arends and McCormick, 1987), and changes in harvesting methods (Abrams and Nowacki, 1992).

Increasingly, managers in the Appalachian forest region are using fire as a management tool with multiple objectives (Brose et al., 2001). A primary objective of prescribed burning in

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upland oak forests is to improve oak regeneration and enhance the likelihood of maintaining oak dominance of these forests, yet the window of opportunity may be closing for reversing the trend in shifting species composition with the application of prescribed fire alone (Abrams, 2005). Fire may assist oak regeneration by reducing the density of fire-sensitive species and opening the canopy to allow light to the forest floor (Lorimer et al., 1994; Barnes and Van Lear, 1998). Many oak seedlings survive fire by sprouting from the rootstock, and in some cases the sprouts may be stronger and straighter than before (Brose and Van Lear, 1998). Prescribed fire also consumes litter, potentially providing a more favorable environment for germinating acorns (Van Lear and Watt, 1993). Because the bark of mature oaks is thick and can protect stems from fire damage (Hengst and Dawson, 1994), prescribed fire may preferentially kill fire-sensitive species without harming standing oaks (Brose, 1999). Fire also causes sprouting of midstory trees after topkill, including fire-sensitive species such as red maple, thereby altering stand structure without increasing light to the forest floor (Chiang et al., 2005). Almost certainly, if prescribed fire is to emerge as an effective tool for management of oak forests it will require multiple fires that eventually kill maples and other competitors. The effects of repeated prescribed fire, in the absence of forest thinning, have not been well-documented in the central Appalachians.

In this study we compared stand dynamics over 9 years in fire-excluded stands and stands with multiple prescribed fires conducted at different intervals in upland oak sites on the Cumberland Plateau. We examined the effect of fire and fire exclusion on stand composition and structure, including changes in basal sprouting and regeneration.

2. Methods

2.1. Site description

The study sites are located on three noncontiguous ridge tops (approximately 360–400 m elevation) in the Stanton Ranger District of the Daniel Boone National Forest in Powell, Menifee, and Wolfe Counties, Kentucky, USA. The ridges are in the Red River Gorge Geological Area in the Cliff Section of the Cumberland Plateau (Braun, 1950). Established in 1937 as the Cumberland National Forest, the purchase unit was described in 1930 as supporting ‘‘hardwood mixtures in which hemlock is sparingly represented on the lower moist sites and pitch, yellow and scrub pine sparingly on the higher dry sites, white pine sparingly on Red River watershed’’ (Collins, 1975, p. 195). The forest condition at that time was described as ‘cutover’ or ‘heavily culled’ (Collins, 1975). The stands on these ridges are second-growth forests dominated by oaks, particularly scarlet oak (*Quercus coccinea* Muench.) and chestnut oak (*Q. prinus* L.), with some black oak (*Q. velutina* Lam.) and white oak (*Q. alba* L.). Hard pines, shortleaf (*Pinus echinata* Mill.) and pitch (*P. rigida* Mill.) pine are also found in dominant canopy positions. The midstory is predominantly composed of red maple, with an abundance of eastern white pine (*P. strobus* L.), sourwood (*Oxydendrum arboreum* [L.] DC), and blackgum (*Nyssa sylvatica* Marsh.). No forest management or unplanned fire has occurred on these study sites for at least the last 25 years (Jorge Hersel, USDA For. Ser., Stanton, Ky., personal communication). The oaks in these stands are approximately 70 years old, while the red maples are approximately 50 years old (Washburn and Arthur, 2003). Site index on these sites is estimated at SI 70 (J. Lewis, Daniel Boone National Forest, personal communication).

Shales and siltstones of the Upper and Lower members of the Lee Formation compose the geological substrate of these ridges—Klaber, Pinch-Em-Tight and Whittleton (Weir and Richards, 1974). Klaber Ridge soils are classified as Latham-Shelocta silt loam, moderately deep, moderately well-drained, slowly permeable clayey soils of the subgroups Typic and Aquic Hapludults (Avers et al., 1974). Pinch-Em-Tight Ridge soils are of Alticrest-Ramsey-Rock outcrop complex, moderately deep and shallow, well-drained with surface layer and subsoil of sandy loam, and are Typic and Lithic Dystrochrepts (SCS, 1975; Hayes, 1993). Whittleton Ridge soils are Gilpin silt loam, a moderately deep, well-drained soil with a lower subsoil of silty clay loam of the subgroup Typic Hapludult (Hayes, 1993). Mean annual precipitation is 130 cm, with a mean growing season of 176 days. Mean annual temperature is 12 °C, with mean daily temperatures ranging from 0 °C in January to 31 °C in July (Foster and Conner, 2001).

2.2. Experimental design and burn regime

In 1995, three ridges were selected as replicates for examining the effects of fire. Ridges were selected in collaboration with USDA Forest Service personnel to meet both research and management criteria: an abundance of eastern white pine in the understory, which provided clear evidence of the absence of fire (Wehner, 1991); accessibility to fire crews; and completed environmental impact assessments. Each ridge was divided into three treatment units with the following treatments: (1) fire-excluded; (2) to be burned initially in 1995; and (3) to be burned initially in 1996. Treatment units averaged 18 ha each on Whittleton and Pinch-Em-Tight ridges; treatment units on Klaber Ridge were larger and averaged 36 ha each. After the first prescribed burns, treatment units were burned subsequently in an adaptive management approach. Because of the location of Whittleton Ridge near a highway, wind conditions conducive to smoke control were not always available, and the unit intended for initial burn treatment in 1996 was burned for the first time in 1997. The 1996 burn treatment on Pinch-Em-Tight Ridge was abandoned as a study unit in 2001 due to impacts of campers on the study plots. Thus, in 2003 our experimental design consisted of three fire-excluded units (one on each ridge), three units burned 2× (one on each ridge), and two units burned 3× (one on Klaber and one on Whittleton ridge).

USDA Forest Service personnel of the Stanton Ranger District conducted all prescribed fires. Firing from the highest points and ridges first, ignition was by drip torch, pulling downslope from the ridges into the wind, and burning across the entire treatment area. Point-source and strip-firing were used if backing and flanking fires were not sufficiently intense (>0.3 m flame length; Richardson, 1995). Flame temperatures were measured with pyrometers made by painting Tempilac® temperature-sensitive paints on aluminium tags attached to stakes at 15 cm above ground and on mica sheets at the surface. Temperatures were measured at four locations in each plot.

From 1995 to 2000, prescribed fires were conducted between March 13 and 31. Recognition of the need to implement early growing season fires resulted in later fires in 2002 (April 15). All fires were characterized as low-intensity surface fires. Fires were conducted when relative humidity was between 25 and 45% and air temperatures were between 8 and 23 °C. Flame heights were generally less than 1 m. Average fire temperatures at the forest floor surface ranged from 109 to 332 °C. Fires temperatures generally increased slightly with successive burns, which may be attributed to increasing fuel above the surface from small-diameter trees top-killed in earlier fires.

2.3. Data collection

In 1995, prior to the first prescribed fires, 100 m^2 circular plots were established for measurement of all stems >2.0 cm DBH. Plots were randomly placed on a map and then located in the field. All plots are located on ridge tops, and any locations within 15 m of a trail or shoulder were rejected. Eight plots were established in each treatment unit on Klaber and Whittleton Ridges. Only six plots were established in each treatment unit of Pinch-Em-Tight Ridge due to the narrowness of the ridge and the abundance of trails traversing it. Center points of plots were permanently marked with rebar and GPS coordinates recorded. Eastern white pine stems of all sizes were measured in 500 m^2 circular plots centered on the 100 m^2 plots in support of a previous study focusing on fire and white pine (Blankenship and Arthur, 1999). Beginning in 1998, the 500 m^2 circular plots were used for measurements of all trees ≥2.0 cm DBH, thereby expanding the measurement area from 100 to 500 m^2. Beginning in 1995, measurements included tree species, DBH, and alive or dead status. Beginning in 1997, number of basal sprouts per stem was added.

Centered on the midpoint of each 500 m^2 plot was a 25 m^2 circular plot established for monitoring woody regeneration <2.0 cm DBH. All stems <2.0 cm DBH were counted and recorded by species. Beginning in 1999, stems <2.0 cm DBH were further subdivided into two height classes, with those <50 cm tall recorded as "seedling-layer" and those ≥50 cm tall recorded as "sapling-layer."

Measurements were made in all plots in late-winter 1995 before burning, and re-measured intermittently in subsequent years with the most recent measurements conducted in fall 2003.

2.4. Data analysis

Pre-burn differences in density and basal area among treatment units were tested with analysis of variance. If the overall F-test was significant, least square means were used to determine differences among treatment units. Significance was determined with $\alpha = 0.10$ because of low sample size and pre-burn variability among ridge sites and treatment units.

To test for changes in stem density and basal area due to treatment, two types of statistical analyses were performed. First, paired t-tests, which paired each ridge/treatment combination in 1995 to itself in 2003, were used to test for treatment effects on changes in density and basal area from 1995 to 2003. For this, analysis was based on fire-excluded or burned treatments, regardless of timing or number of burns, presenting a design with $n = 5$ for burned treatments and $n = 3$ for fire-excluded treatments. Stems were divided into midstory (2–10 cm DBH) and overstory (≥10 cm DBH) for density and basal area analyses, as well as by size class (2–5 cm DBH, then 5 cm size class increments) for a more detailed analysis of stem density changes over time. Post-burn stem density and basal area of midstory stems (2–10 cm DBH) did not meet assumptions of normality and were therefore tested using the Wilcoxon signed-rank test. Changes in stem density over 9 years were also analyzed for all species combined as well as by individual species or, in some cases, species groups. White oak, scarlet oak, chestnut oak, and black oak were analyzed individually as well as together as a group including southern red oak and post oak. The 'hard pine' species (*P. echinata*, *P. rigida* and *P. virginiana*) were also grouped together because of small numbers present on the sites. All other species that occurred in small numbers were also grouped together (*Amelanchier arborea* (Michx. F.) Fern., *Carya glabra* (Miller), *C. tomentosa* (Poiret) Nutt., *C. dentata*, *Diospyros virginiana* L., *Fagus grandifolia* Ehrh., *Juniperus virginiana* L., *Kalmia latifolia* L., *Liriodendron tulipifera* L., *Magnolia acuminata* (L.) L., *Magnolia macrophylla* (Michx.), *Sassafras albidum* ((Nutt.) Nees, and *Tsuga canadensis* (L.) Carriere).

Secondly, to compare changes in stem density based on the time since burning rather than on the calendar year, density data were grouped according to the number of growing seasons elapsed since a fire event. Paired t-tests were used to (1) compare pre-burn to two, three and four growing seasons after a single prescribed fire; (2) to compare pre-burn to one, two, three and four growing seasons after a second prescribed fire; and (3) to compare pre-burn to two growing seasons after a third prescribed fire. Since measurements were not made on all units in every year, and since fires occurred during different years, the sample size for each test varied (Table 1). Each test used only the units that had data for both time periods (e.g., pre-burn to two growing seasons after three fires used only the units that burned 3×), so the combination of units and years varied from test to test. Tests were conducted on size classes of 2–10 cm DBH, 10–20 cm DBH, and >20 cm DBH. No further subdivision of size classes was done, since the fires did not affect size classes greater than 20 cm DBH.

We also analyzed basal sprouts by grouping the data in the same way: comparing sprout density and sprouts per stem according to the time elapsed since the last fire event. As sprouts were first measured in 1997 on overstory trees ≥2.0 cm DBH, and the 3×-burned treatments were the only treatments with measurements consistently made in the same time periods

Table 1a
Year that each unit was burned and the corresponding number of growing seasons since the last prescribed fire event used in stem density paired *t*-test analyses

Ridge	Treatment	Year	# Growing seasons since last fire event
Klaber	3×-burned	**1995**	Pre-burn
		1996	2 post 1 fire
		1997	3 post 1 fire
		1998	4 post 1 fire
		1999	1 post 2 fires
		2000	1 post 3 fires
		2001	2 post 3 fires
		2003	4 post 3 fires
Klaber	2×-burned	1995	Pre-burn
		1996	1 post 1 fire
		1997	2 post 1 fire
		1999	4 post 1 fire
		2000	1 post 2 fires
		2001	2 post 2 fires
		2003	4 post 2 fires
Pinch-Em-Tight	2×-burned	**1995**	Pre-burn
		1996	2 post 1 fire
		1997	3 post 1 fire
		1998	4 post 1 fire
		1999	1 post 2 fires
		2001	3 post 2 fires
		2003	5 post 2 fires
Whittleton	3×-burned	**1995**	Pre-burn
		1996	2 post 1 fire
		1997	3 post 1 fire
		1998	4 post 1 fire
		1999	1 post 2 fires
		2000	2 post 2 fires
		2001	3 post 2 fires
		2002	No data
		2003	2 post 3 fires
Whittleton	2×-burned	1995	pre-burn
		1997	No data
		1999	3 post 1 fire
		2000	4 post 1 fire
		2002	No data
		2003	2 post 2 fires

Years when a unit was burned are in bold. Years not listed are years in which no data were collected for that unit.

Table 1b
Sample size (*n*) for paired *t*-test analyses on stem density by number of growing seasons since last prescribed fire event

Test	*n*
2 growing seasons post 1 fire	4
3 growing seasons post 1fire	4
4 growing seasons post 1fire	5
1 growing seasons post 2 fires	4
2 growing seasons post 2 fires	3
3 growing seasons post 2 fires	2
4 or 5 growing seasons post 2 fires	2
2 growing seasons post 3 fires	2

Table 1a shows which year each unit was burned and when data were collected.

since fire events (Table 1), paired *t*-test analyses used only the two 3×-burned treatments to compare three and four growing seasons after one prescribed fire, one growing season after two prescribed fires, and two growing seasons after three prescribed fires. Changes in density (sprouts/ha) were analyzed for total sprouts (all species combined); and red maple, sourwood, blackgum, and oak species (as a group) were analyzed separately. Differences among red maple, sourwood, blackgum, and oak species were analyzed by comparing mean number of sprouts/stem (the number of sprouts from a single tree) within a specified growing season.

In 2003, basal sprouts were also counted in the regeneration plots for an additional measurement of sprout density. We added this measurement because the previous count of sprouts taken with overstory measurements focused on sprout clumps associated with tree stems ≥2.0 cm DBH, and any basal sprouts connected to tree stems <2.0 cm DBH were overlooked in the overstory measurements. The additional measure of basal sprout density was analyzed by comparing density among the treatments in 2003 (fire-excluded ($n = 3$), 2×-burned ($n = 3$), and 3×-burned ($n = 2$)), using the Tukey–Kramer HSD test (Sall et al., 2005).

To test the effects of fire and fire-exclusion on tree regeneration (defined as stems <2.0 cm DBH), data were analyzed in two ways. First, paired *t*-tests were used to compare changes in stem density from fall of 1995–2003 on burned ($n = 2$) and fire-excluded ($n = 3$) treatments. We did not use the pre-burn data for the 1995 burned treatments because the measurements were made in January 1995, when seedlings were difficult to see and identify. Therefore, we compared changes over the 9 years only on the burned units that had robust pre-burn data, which were the 2×-burned units on Klaber and Whittleton. Secondly, to compare regeneration densities in 2003 among the different treatments—fire-excluded ($n = 3$), 2×-burned ($n = 3$), and 3×-burned ($n = 2$), we used the Tukey–Kramer HSD test (Sall et al., 2005).

All statistical analyses were run using JMP IN® statistical software for Macintosh (SAS Institute, Inc., 2003).

3. Results

3.1. Pre-burn stand structure

Mean overstory (stems ≥10 cm DBH) density was 610 stems/ha and mean basal area was 26 m^2/ha in 1995. On all units, oaks dominated the overstory in both relative density (46–69%) and relative basal area (51–85%; Table 2). Red maple generally had the second highest relative density and/or relative basal area, followed by hard pine species. On one unit, eastern white pine had second highest relative density and basal area. Pre-burn density of overstory hard pines was significantly higher on the Pinch-Em-Tight 2×-burned ($p = 0.05$) unit than on the other units; no other significant differences among units existed in overstory pre-burn density and basal area.

Mean density of midstory stems (2–10 cm DBH) was 1557 stems/ha and mean basal area was 3.6 m^2/ha. In stark contrast to overstory species composition, oak mean relative stem density in the midstory (which included chestnut oak and

Table 2
Relative density and basal area (%) and total density (stems/ha) and basal area (m^2/ha) of stems ≥10 cm DBH measured prior to burning in 1995 and in 2003 on all units on three ridges in the Daniel Boone National Forest, Kentucky

Species	Fire-excluded						Burned twice						Burned three times			
	Klaber		Pinch-Em-Tight		Whittleton		Klaber		Pinch-Em-Tight		Whittleton		Klaber		Whittleton	
	1995	2003	1995	2003	1995	2003	1995	2003	1995	2003	1995	2003	1995	2003	1995	2003
Acer rubrum	25	40	12	32	21	41	23	13	3	1.6	15	25	31	18	7.8	7.9
Carya spp.[a]	2.2	2.3	0	0	2.2	0.49	0	0.49	8.9	4.8	0	0.50	1.9	3.1	3.9	0.66
Nyssa sylvatica	6.3	4.5	0	1.6	0	3.9	0	4.4	0	0	0	1.5	1.9	1.8	0	0
Oxydendrum arboreum	4.2	1.4	12	6.8	6.3	2.9	1.9	4.9	0	0.81	6.3	4.5	1.9	6.7	7.8	2.6
Pinus spp.[b]	13	3.2	12	5.7	2.2	0	5.8	3.9	29	27	2.2	1.0	0	0	6.0	4.6
Pinus strobus	4.2	4.1	12	18	0	2.4	0	3.9	3.0	10	2.2	1.5	9.6	5.5	6.0	1.9
Quercus spp.[c]	46	43	51	36	65	48	69	69	56	55	69	64	52	64	69	82
Other spp.[d]	0	1.8	0	0.52	4.2	1.5	0	0	0	0.81	6.5	1.5	1.9	0.61	0	0
Total density (stems/ha)	600	550	550	640	600	513	650	508	567	413	600	498	650	408	638	378
% Change	−8%		16%		−15%		−22%		−27%		−17%		−37%		−41	
Acer rubrum	8.4	15	2.6	12	9.6	15	13	6.2	0.89	0.46	5.5	10	13	8.6	3.2	2.7
Carya spp.[a]	0.30	1.4	0	0	6.8	1.6	0	0.71	2.4	1.4	0	0.11	0.52	5.3	0.40	0.12
Nyssa sylvatica	13	7.3	0	0.55	0	1.0	0	2.2	0	0	0	0.37	0.42	0.44	0	0
Oxydendrum arboreum	0.65	0.29	2.7	2.1	2.3	0.71	0.74	1.2	0	0.16	3.3	1.6	0.39	2.0	1.6	0.64
Pinus spp.[b]	25	6.8	17	11	3.6	0	9.5	5.1	27	24	2.2	2.4	0	0	6.1	8.3
Pinus strobus	1.1	2.4	18	5.8	0	0.51	0	1.9	2.1	11	0.91	1.1	5.8	3.3	2.0	0.69
Quercus spp.[c]	51	67	60	68	78	81	75	82	67	63	84	84	78	81	79	87
Other spp.[d]	0	0.59	0	0.18	0.89	0.62	0	0	0	0.8	1.9	0.73	0.32	0.25	0	0
Total basal area (m^2/ha)	31	27	30	27	28	26	19	25	18	19	22	24	31	23	30	21
% Change	−13%		−10%		−7.1		32%		5.6%		10%		−26%		−30%	

For each unit, years with prescribed fires are listed in Table 1.
[a] *Carya* spp. include *Carya glabra* and *C. tomentosa*.
[b] *Pinus* spp. include *Pinus echinata*, *P. rigida*, and *P. virginiana*.
[c] *Quercus* spp. include *Quercus alba*, *Q. coccinea*, *Q. prinus*, and *Q. velutina*.
[d] Other spp. include *Liriodendron tulipifera*, *Magnolia acuminata*, *M. macrophylla*, *Sassafras albidum*, and *Tsuga canadensis*.

very small numbers of white oak only; no scarlet or black oak stems) was 5% and mean relative basal area was 7% (Table 3). Red maple was either dominant in the midstory or co-dominant with eastern white pine, and had higher mean relative density (45%) and basal area (44%) than all other species (Table 3). Eastern white pine had average relative density in the midstory of 14% and basal area of 15%. Blackgum and sourwood were well represented on all units.

3.2. Stand structure in 2003: nine more years of fire exclusion

In the absence of fire, overstory basal area (≥10 cm DBH) decreased 10% from 30 to 27 m^2/ha ($p = 0.01$), but overstory density did not significantly decrease because stem density of some species decreased while others increased (Table 2). Red maple stem density ≥10 cm DBH increased 85% from 114 to 211 stems/ha ($p = 0.04$). When broken down by size class, the increase was significant only in the 10–15 cm DBH size class ($p = 0.02$; Fig. 1(A)), although all other overstory size classes up to 40 cm DBH increased non-significantly. Basal area of red maple stems ≥10 cm DBH increased 85%, from 2.0 to 3.7 m^2/ha ($p = 0.05$). Blackgum density also increased 3.6 stems/ha in the 15–20 cm DBH size class ($p = 0.04$). Conversely, oak stem density decreased 55% in the 10–15 cm DBH size class ($p = 0.02$) and generally was not balanced by increases in larger size classes. Decreases in oak density were primarily in white oaks, which declined 65% in stems ≥10 cm DBH. Sourwood overstory stem density also decreased (49%; $p = 0.01$; Table 2).

On the fire-excluded units, overall stem density and basal area of midstory stems (2–10 cm DBH) decreased over the 9 years of this study. Midstory stem density decreased 24% between 1995 and 2003, from 1646 to 1246 stems/ha ($p = 0.04$; Fig. 1(B); Table 3), and midstory basal area decreased 28% from 4.0 to 2.9 m^2/ha ($p = 0.01$; Table 3). Red maple midstory density decreased 39% from 704 to 429 stems/ha ($p = 0.004$; Fig. 1(A)). The few white oak stems measured in 1995 (19 stems/ha) were gone by 2003. Due to dogwood anthracnose (*Discula destructiva*), flowering dogwood (*Cornus florida*) decreased dramatically in density (98%; $p = 0.01$) and basal area (97%; $p = 0.02$). Decreases in midstory stems may have partly resulted from competition with small-diameter eastern white pine, whose density increased 26% (although not significantly; $p = 0.43$) in the 2–5 cm DBH class from 269 to 362 stems/ha. Moderate drought conditions in 1998 and severe

Table 3
Relative density and basal area (%) and total density (stems/ha) and basal area (m^2/ha) of stems 2–10 cm DBH measured prior to burning in 1995 and in 2003 on all units on three ridges in the Daniel Boone National Forest, Kentucky

Species	Fire-excluded						Burned twice						Burned three times			
	Klaber		Pinch-Em-Tight		Whittleton		Klaber		Pinch-Em-Tight		Whittleton		Klaber		Whittleton	
	1995	2003	1995	2003	1995	2003	1995	2003	1995	2003	1995	2003	1995	2003	1995	2003
Acer rubrum	43	43	31	23	68	56	45	38	25	24	42	42	25	25	66	8.3
Carya spp.[a]	0.90	1.3	0.70	0.16	0	0.58	2.1	2.6	4.7	8.0	1.1	2.8	1.7	0	0.70	8.3
Cornus florida	12	0.66	5.4	0.16	9.7	0	3.4	2.6	7.8	0	14	0	25	0	5.1	0
Nyssa sylvatica	8.5	11	4.8	3.5	9.7	14	18	24	4.7	0	18	34	16	47	12	58
Oxydendrum arboreum	4.7	4.9	6.1	1.4	3.2	3.5	16	17	7.8	8.0	5.4	13	5.0	8.3	8.0	0
Pinus spp.[b]	0	0	0.70	0.94	0	0	0	0	16	20	0	0	0	0	0	0
Pinus strobes	25	34	48	66	9.7	21	7.6	6.4	14	14	5.4	1.4	22	5.6	1.4	0
Quercus spp.[c]	1.9	0.66	2.7	0.47	0	0	2.8	7.7	16	22	4.3	4.2	5.0	14	4.3	17
Other spp.[d]	3.8	4.0	1.4	4.9	0	5.2	5.6	1.3	4.8	4.0	9.7	2.8	1.7	0	2.2	8.3
Total density (stems/ha)	1325	758	2450	2123	1163	858	1813	195	1067	167	1163	178	1513	90	1725	30
% change	−43%		−13%		−26%		−89%		−84%		−85%		−94%		−98%	
Acer rubrum	57	48	30	30	69	67	41	24	18	8.3	46	46	25	8.5	63	20
Carya spp.[a]	1.0	2.0	1.7	0.44	0	1.5	3.8	3.9	9.2	14	1.5	2.8	1.2	0	0.74	17
Cornus florida	8.5	0.53	5.2	0.49	14	0	1.3	0.51	16	0	18	0	19	0	2.8	0
Nyssa sylvatica	4.8	5.8	2.2	2.4	4.6	12	14	24	2.2	0	13	27	9	55	4.7	38
Oxydendrum arboreum	4.0	6.6	11	2.9	4.2	3.6	23	24	5.9	7.7	2.1	12	7.2	7.9	14	0
Pinus spp.[b]	0	0	0.48	1.6	0	0	0	0	23	27	0	0	0	0	0	0
Pinus strobes	18	32	44	58	7.9	14	8.4	8.3	8.8	15	3.8	2.4	26	3.8	0.50	0
Quercus spp.[c]	1.6	1.6	4.7	0.86	0	0	5.8	13	16	26	6.0	6.8	12	25	8.7	24
Other spp.[d]	5.1	3.4	0.40	2.6	0	2.8	3.3	1.4	0.81	1.7	9.2	3.7	0.80	0	2.5	1.4
Total Basal Area (m^2/ha)	3.1	1.8	6.0	5.1	2.8	1.9	4.8	0.74	1.9	0.47	2.6	0.74	3.8	0.29	4.0	0.090
% Change	−42%		−15%		−32%		−85%		−75%		−72%		−92%		−98%	

Dates of prescribed fires are listed in Table 1.

[a] *Carya* spp. include *Carya glabra* and *C. tomentosa*.

[b] *Pinus* spp. include *Pinus echinata*, *P. rigida*, and *P. virginiana*.

[c] *Quercus* spp. include *Quercus alba*, *Q. coccinea*, *Q. prinus*, and *Q. velutina*.

[d] Other spp. include *Liriodendron tulipifera*, *Magnolia acuminata*, *M. macrophylla*, *Sassafras albidum*, and *Tsuga canadensis*.

drought conditions in 1999 also may have contributed to decreases in midstory density over the 9 years.

3.3. Effects of burning: midstory (2–10 cm DBH)

Between 1995 and 2003, midstory (2–10 cm DBH) stem density on burned units decreased 91% on average (1504–132 stems/ha; $p = 0.06$) and basal area decreased 86% (3.4–0.47 m^2/ha; $p = 0.06$; Table 3). Flowering dogwood decreased the most in density (99%; $p = 0.06$) and basal area (100%; $p = 0.06$), even more so than on the fire-excluded units. Midstory red maple had the next largest reduction in stem density (95%; $p = 0.06$, and midstory red maple basal area decreased 91% ($p = 0.06$)). Midstory oak stem density decreased 82% ($p = 0.06$), primarily in the 5–10 cm DBH class, and basal area of midstory oaks decreased 68% ($p = 0.06$). The only oak species present in the midstory, chestnut and white oaks, both declined, with white oaks declining to 0 stems/ha. The "other species" group decreased in both the 2–5 cm and 5–10 cm DBH size classes ($p = 0.06$), while blackgum, sourwood and eastern white pine decreased only in the 2–5 cm DBH class ($p = 0.06$ for each).

The analysis of density by number of growing seasons since fire revealed an interesting pattern in mortality and recovery of midstory stems (Fig. 2). Two growing seasons after a single prescribed fire, midstory density decreased 63% from pre-burn density (from 1558 to 571 stems/ha; $n = 4$; $p = 0.02$). Midstory density continued to decrease in the third growing season after a single fire to 296 stems/ha (79% decrease from pre-burn, $n = 4$; $p = 0.01$), but began to increase again after four growing seasons to 395 stems/ha, still significantly less than pre-burn stem density (74% decrease, $n = 5$; $p = 0.002$). A second prescribed burn reduced midstory density 87% from pre-burn levels to 204 stems/ha ($n = 4$; $p = 0.005$; Fig. 2). As after one fire, density continued to decrease after the second (to 135 stems/ha, $p = 0.02$) and third growing seasons (to 93.5 stems/ha, $n = 2$; $p = 0.18$), but began to increase after the fourth growing season to 181 stems/ha ($n = 2$; $p = 0.17$). Two growing seasons after a third fire, total midstory density was reduced 96% from pre-burn levels to 68 stems/ha ($n = 2$; $p = 0.32$).

Analysis of midstory red maple density by number of growing seasons since fire revealed a similar pattern to that of total midstory density (Fig. 2). Two growing seasons after a single prescribed fire, midstory red maple density had decreased 78% from 677 to 148 stems/ha ($n = 4$; $p = 0.08$), and three growing seasons later had decreased 89% from pre-burn densities to 69 stems/ha ($n = 4$; $p = 0.06$). By the fourth growing season after a single fire, red maple began to increase to 132 stems/ha, but was still 80% lower than pre-burn densities

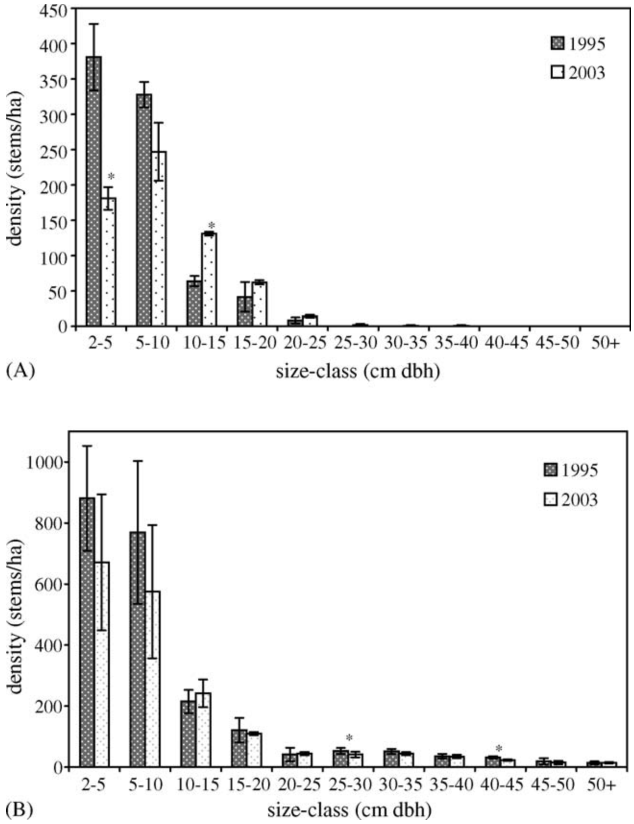

Fig. 1. Mean stem density (stems/ha) by size class (cm DBH) on fire-excluded units ($n = 3$) in the Daniel Boone National Forest, Kentucky, in 1995 and 2003 (A) for red maple, and (B) for all species. Error bars represent S.E.M. Asterisks denote significant differences between 1995 and 2003.

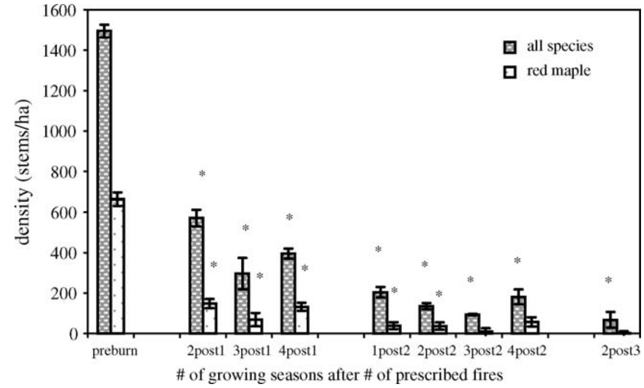

Fig. 2. Mean midstory (2–10 cm DBH) stem density for all species together and red maple separately by number of growing seasons since the last prescribed fire event on burned units in the Daniel Boone National Forest, Kentucky. Details of this analysis are listed in Table 1. Error bars represent S.E.M. Asterisks denote significant differences between pre-burn 1995 and the time denoted on the x-axis.

($n = 5$; $p = 0.02$). Two prescribed fires further reduced midstory red maple stems compared to a single fire, and one growing season after a second fire, midstory red maple had decreased 94% from pre-burn levels to 39 stems/ha ($n = 4$; $p = 0.04$). Density continued to decrease over the next two growing seasons, declining 96% in the second growing season ($n = 3$; $p = 0.04$) and, although not significant, 99% by the third growing season to 9 stems/ha ($n = 2$; $p = 0.36$). Again, four growing seasons after the second fire, red maple midstory density began to increase to 58 stems/ha. Three fires almost completely eliminated red maple midstory trees. Two growing seasons after a third prescribed burn, red maple stem density averaged only 2.5 stems/ha, a 99.7% reduction since 1995 ($n = 2$; $p = 0.24$), although this additional increase in mortality was statistically insignificant due to the small sample size ($n = 2$) and variability. Four growing seasons after the third burn, red maple density had increased to 23 stems/ha on Klaber Ridge, the only 3×-burn treatment for which we had data four growing seasons after burning.

Using the same analysis by growing season since burning, midstory eastern white pine stems decreased after each fire event. Two growing seasons after a single burn, density decreased 51% from 160 to 78 stems/ha ($n = 4$; $p = 0.02$), then to 51 stems/ha ($n = 4$; $p = 0.06$) after three growing seasons, and after four growing seasons averaged 47 stems/ha ($n = 5$; 66%, $p = 0.05$). A second burn reduced eastern white pine stems 83% to 28 stems/ha ($n = 4$; $p = 0.04$) the first growing season, and 88% to 18 stems/ha ($n = 2$; $p = 0.002$) after the fourth growing season. A third prescribed burn reduced eastern white pine stems in the midstory to an average of 5 stems/ha ($n = 2$; $p = 0.22$); this further reduction was not statistically significant due to the small sample size.

Oak midstory stem density decreased with burning as well, but not as dramatically with a single fire. Oak species only had a relative density of <5% in the midstory prior to burning. Two growing seasons after a single fire, oak stem density decreased 43% from 92 to 52 stems/ha ($n = 4$; $p = 0.05$). The decline continued to 38 stems/ha after three growing seasons ($n = 4$; $p = 0.02$), and to 33 stems/ha after four growing seasons ($n = 5$; $p = 0.05$). Two fires decreased oak midstory density by 74% compared to pre-burn density ($n = 4$; 24 stems/ha, $p = 0.04$) by the first growing season. Density continued to decrease three and four growing seasons after the second burn to 23 stems/ha, but the additional decline was not significant ($n = 2$; $p = 0.17$). Two growing seasons after a third fire, oak midstory density averaged 15 stems/ha ($n = 2$; $p = 0.05$).

3.4. Effects of burning: overstory (≥10 cm DBH)

Between 1995 and 2003 overstory stem density decreased 30% (626–441 stems/ha; $p = 0.003$) on the burned units, compared to no significant change in the fire-excluded units (Table 2), but these changes were predominantly in trees between 10 and 20 cm DBH. These prescribed fires did not significantly affect mortality of trees ≥20 cm DBH.

Overstory oak stem density decreased 25% on burned units, from 391 to 294 stems/ha ($p = 0.0004$). The oak species that decreased the most was white oak (62%, $p = 0.11$), but the only significant decrease was in scarlet oak stem density (49%, $p = 0.05$). The greatest loss of oak species was in the 10–15 cm DBH size class (43%, $p = 0.01$). This size class decreased on the fire-excluded units as well, where the loss was greater at 55%.

There was no significant change in basal area for overstory species on the burned units ($p = 0.59$; Table 3), whereas a 10% reduction in basal area on the fire-excluded units was significant ($p = 0.01$). When the 2×-burned units were compared to the 3×-burned units, overstory basal area did not significantly change on the 2×-burned units ($p = 0.59$), but decreased 28% (from 31 to 22 stems/ha; $p = 0.05$) on the 3×-burned units (Table 3).

When analyzed by number of growing seasons after burning, stems 10–20 cm DBH followed a pattern similar to that of stems in the midstory. In this size class, stem density decreased with each successive season after one fire until the fourth growing season, in which a slight increase occurred. However, the only significant change was a 25% decline in stem density from pre-burn to four growing seasons later ($n = 5$; $p = 0.01$). After two burns, density decreased 34% after one growing season ($n = 4$; $p = 0.01$), and remained 34% lower after two growing seasons ($n = 3$; $p = 0.03$) and then declined further by the third growing season, but not significantly ($n = 2$). Four growing seasons after a second fire, density was 47% lower than pre-burn density ($n = 2$; $p = 0.05$), although stem density increased from the year before (from 177 to 207 stems/ha). After three fires, 10–20 cm DBH stem density had decreased 45% to 192 stems/ha ($n = 2$; $p = 0.095$).

The decrease in stem density of stems 10–20 cm DBH was generally not attributable to significant reductions in individual species. Eastern white pine stem density in this size class did not decrease significantly until after three fires, when density had decreased 68% from 44 to 14 stems/ha ($n = 2$; $p < 0.0001$). Oak stems 10–20 cm DBH decreased after burning, but the decrease was only significant four growing seasons after one fire (16%; $n = 5$; $p = 0.095$), and four growing seasons after a second fire (53%, from 209 to 98 stems/ha; $n = 2$; $p = 0.04$).

3.5. Sprouting

Multiple fires killed many small-diameter stems, but also caused top-killed and wounded stems to produce basal sprouts. The highest density of basal sprouts (8217 sprouts/ha measured on trees ≥2.0 cm DBH) occurred after the third prescribed fire, although it was not significantly different from sprout density after one ($p = 0.73$) or two fires ($p = 0.44$) due to high spatial variability (Fig. 3). Sprout density declined from three to four growing seasons after one prescribed burn, but then increased again after each subsequent fire (Fig. 3). Red maple comprised the greatest proportion of basal sprouts (60–71% of total sprouts) and significant changes in red maple basal sprout density dominated the changes in total basal sprout density (Fig. 3). Red maple trees also had the highest average number of basal sprouts/stem, followed by sourwood, blackgum, and oaks (Fig. 4), although species differences were not always significant. The number of red maple basal sprouts/stem increased with each additional fire in a pattern similar to that for sprout density, although not significantly (Fig. 4). Oak basal sprouts/stem did not consistently increase after successive fires. Blackgum and sourwood sprouts/stem

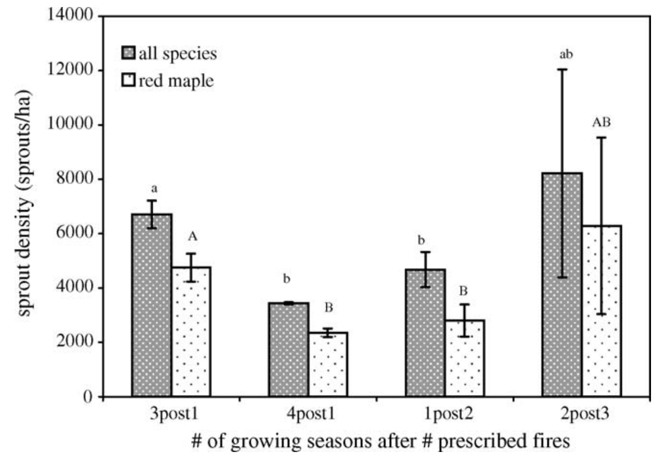

Fig. 3. On units burned 3× in the Daniel Boone National Forest, Kentucky, mean sprout densities (stems/ha) for all species together and red maple separately are shown by the number of growing seasons since the last prescribed fire event. Details of this analysis are listed in Table 1. Error bars represent S.E.M. Different lowercase letters denote significant differences in sprout density of all species combined between growing seasons, and different uppercase letters denote significant differences in red maple sprout density between growing seasons.

increased after the second fire, but after three fires, the average basal sprouts/stem was about the same as after two fires.

Comparisons among treatments of basal sprout density measured in the regeneration plots in 2003 showed that the 3×-burn units had the highest density (14,275 sprouts/ha; $p = 0.05$). The 2×-burn units had basal sprout density of 7794 sprouts/ha and the fire-excluded units had 1405 sprouts/ha. Red maple basal sprouts were highest on the 3×-burn treatments ($p = 0.06$), accounting for 76% of the total basal sprout density. In as few as 3 years after fire, some red maple sprouts in a clump moved into the 2–5 cm DBH size class. Although stem density in this size class was still far below pre-burn density, the increase was apparent.

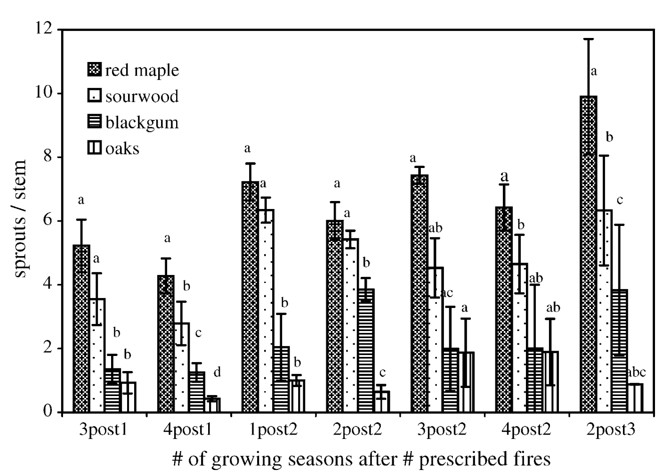

Fig. 4. On units burned 3× in the Daniel Boone National Forest, Kentucky, mean sprouts/stem for red maple, sourwood, blackgum, and oak species are shown by the number of growing seasons since the last prescribed fire event. Details of this analysis are listed in Table 1. Error bars represent S.E.M. Different letters denote significant differences among species within a growing season.

3.6. Regeneration (stems <2.0 cm DBH)

Total stems in the regeneration pool increased on all units from 1995 to 2003, but the increase was significant only on the burned units ($n = 2$, Klaber and Whittleton 2×-burned). Density of stems <2.0 cm DBH increased 336% on burned units by 2003 (from 14,800 to 64,550 stems/ha; $p = 0.02$) compared to fire-excluded units (138%, from 19,072 to 45,328 stems/ha; $p = 0.15$). However, the number of stems <2.0 cm DBH on burned units was not significantly different from those on the fire-excluded units in 2003 ($p = 0.81$).

Red maple stems increased significantly from 1995 to 2003 on fire-excluded (from 7672 to 26,867 stems/ha; $p = 0.02$) and non-significantly on Klaber and Whittleton 2×-burned units (from 6250 to 27,350 stems/ha; $p = 0.38$,). Among treatments, the densities of red maple stems were not significantly different from each other in 2003 (3×-burned: 22,950 stems/ha, $n = 2$; 2×-burned: 20,367 stems/ha, $n = 3$; fire-excluded: 26,867 stems/ha, $n = 3$; $p = 0.86$) (Fig. 5). However, when seedling- (<50 cm tall) and sapling-layer (>50 cm tall and <2.0 cm DBH) stem density data were analyzed separately, the densities of red maple sapling-layer stems were significantly higher on the 3×-burned units (6825 stems/ha) compared to the 2×-burned units (2789 stems/ha) and the fire-excluded units (361 stems/ha; $p = 0.01$). This was a result of the greater basal sprout response on the 3×-burned units, for which basal sprouts in the sapling-layer (6350 sprouts/ha) were significantly greater than those on fire-excluded units (194 sprouts/ha; $p = 0.02$), but not significantly different from 2×-burned units (2194 sprouts/ha) The density of red maple stems in the seedling-layer did not differ by treatment in 2003 ($p = 0.67$).

Eastern white pine was the species in the regeneration pool most negatively affected by fire. Burning eliminated white pine stems in the sapling-layer (>50 cm tall and <2.0 cm DBH). However, due to the variability among the fire-excluded units, comparison of 2003 sapling-layer density among treatments showed no significant differences. Removing the Pinch-Em-Tight fire-excluded unit from the analysis (it was the unit with the highest density of eastern white pine), the difference among treatments was significant for sapling-layer white pine stems, with 225 stems/ha on fire-excluded units and 0 stems/ha on all burned units ($p = 0.02$).

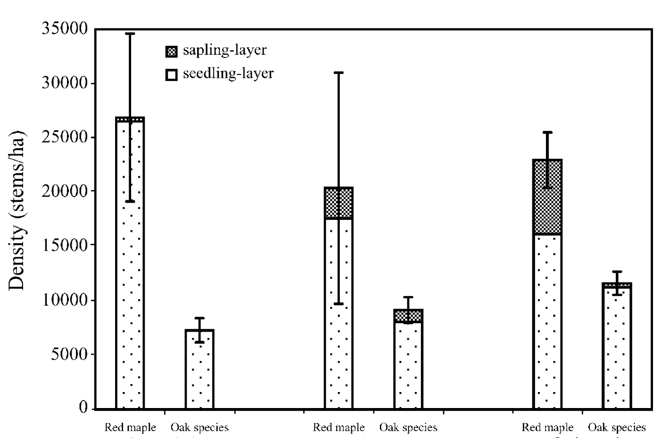

Fig. 5. Density (stems/ha) of red maple and oak stems (<2.0 cm DBH) in the seedling-layer (<50 cm tall) and sapling-layer (>50 cm tall and <2.0 cm DBH) on all units on three ridges in the Daniel Boone National Forest, Kentucky, in 2003. Error bars represent S.E.M for total regeneration (seedling and sapling layers combined).

Oak regeneration increased significantly from 1995 to 2003 on the fire-excluded units (3206–7294 stems/ha; $p = 0.04$) and the Klaber and Whittleton 2×-burned units (from 2375 to 8000 stems/ha; $p = 0.08$). In 2003, stem density of oaks in the seedling-layer was highest on the 3×-burned units (11,250 stems/ha) compared to the 2×-burned units (8067 stems/ha), and the fire-excluded units (7278 stems/ha; $p = 0.13$) (Fig. 3). Higher seedling-layer oak density on the 3×-burned units was not due to basal sprouting; seedling-layer basal sprouts in 2003 were highest on the 2×-burned treatments (561 sprouts/ha versus 50 sprouts/ha on the 3×-burned and 33 sprouts/ha on the fire-excluded treatments; $p = 0.47$). Burning did not affect oak densities in the sapling layer.

Dogwood anthracnose affected flowering dogwood regeneration, which decreased from 1995 to 2003 on all treatments, although not significantly due to variability among units (fire-excluded: from 1267 to 16.7 stems/ha; $p = 0.36$; burned: from 725 to 100 stems/ha; $p = 0.44$). Repeated burning apparently enhanced the regeneration of flowering dogwood. In 2003, the 3×-burned units had significantly higher densities with 925 stems/ha in the seedling-layer (versus 66.7 stems/ha in 2×-burned and 16.7 stems/ha in the fire-excluded; $p < 0.0001$), and 175 stems/ha in the sapling-layer (versus 0 stems/ha in the other treatments; $p = 0.02$).

4. Discussion

Because of awareness of the historic and prehistoric role of fire in maintaining oak stands in the Appalachian region, forest managers have been using prescribed fire for multiple management objectives (Brose et al., 2001). In Kentucky's Daniel Boone National Forest, prescribed fire was reintroduced in response to the growing presence of red maple and eastern white pine. Wehner (1991) first documented the increasing density of eastern white pine in the Daniel Boone National Forest and linked it to effective fire suppression.

This study confirms observations that red maple has moved into the overstory of upland oak stands that have not been burned. The 85% increase in red maple density and basal area on fire-excluded units during the 9 years of this study demonstrates the growing importance of red maple in these oak stands.

Repeated late-winter fires substantially reduced midstory stem density (2–10 cm DBH), and were especially effective in top-killing a large number of red maple and killing eastern white pine stems. When analyzed using the number of growing seasons since burning, a rebound in red maple stem density became evident in the fourth growing season after burning, primarily due to a strong sprouting response. This rebound in stem density did not occur for midstory oaks. Coupled with low midstory oak stem density to begin with, repeated fires negatively affected oak presence in the midstory by knocking stem density down to 15 stems/ha. Elliott et al. (1999) also found decreases in density of oak stems $\geq$5.0 cm DBH following fire on a southern Appalachian ridge, but in contrast to our findings, found increased oak density in the 1–5 cm DBH size class.

As other prescribed fire studies have reported (Blake and Schuette, 2000; Franklin et al., 2003), overstory stems generally were not affected by burning. Blake and Schuette (2000) found that density and basal area of stems >10 cm DBH on burned sites did not differ from that on fire-excluded sites in oak stands in Missouri. Franklin et al. (2003) found no effect of light to moderate fires on stems >3.6 cm DBH. The fires in these studies did not affect stems >20 cm DBH. In this study, oaks in the 10–15 cm DBH class declined more on fire-excluded units than on the burned units. The greater loss of oak stems 10–15 cm DBH on the fire-excluded units could be due to increased competition from fire-sensitive species; conversely the increase in fire-sensitive species in these size classes could be in response to loss of oak stems.

The flowering dogwood populations on these ridges were devastated during the 9 years of this study, presumably from dogwood anthracnose. Slightly higher losses of dogwood stems on burned units may have been the result of stressed and dying trees not withstanding the additional stress of fire. The decline of dogwood stems on fire-excluded units was also very high, suggesting that the eventual loss of flowering dogwood trees in the region may be inevitable. However, much higher density of dogwood regeneration on the 3×-burned treatments indicates that rootstocks survive and fire may be an important process aiding regeneration. Higher densities of dogwood stems were measured in areas that had burned in the Great Smoky Mountains National Park as a result of prolific sprouting (Jenkins and White, 2002). The dogwood regeneration (<2.0 cm DBH) measured on burned units in our study appeared to be of sprout origin, although most were not stump sprouts.

The long-term consequences of repeated burning on oak regeneration are not clear. An earlier study addressing a single prescribed fire (Kuddes-Fischer and Arthur, 2002) found increased oak and red maple regeneration after burning on these ridges. Results of other studies have varied, with either increased (Elliott et al., 1999) or no effect (Reich et al., 1990) on oak seedlings, while also reporting reduced red maple seedling densities (Reich et al., 1990; Elliott et al., 1999). We found higher numbers of oak regeneration on the burned treatments, but red maple stems were higher as well, were present in the sapling layer, and far exceeded the number of oak stems. The higher densities of sapling-layer red maples on burned units were due to large increases in basal sprouts caused by the fires. The increased sprouting created a dense understory layer that can block light for intermediate shade-tolerant species such as oaks (Chiang et al., 2005). Another study in this area, at Gray's Arch, found that repeated fires reduced the density of basal sprouts (Arthur et al., 1998), contrary to the findings in this study. Differing results may have been due to varying intensity of the fires. An escaped campfire caused one of the Gray's Arch fires and likely resulted in a more intense fire than those conducted within prescription parameters for this study. It is possible that higher intensity fires or fires occurring during growing season conditions are necessary to reduce the sprouting capacity of persistent red maple stems (Brose and Van Lear, 1998). Three late-winter fires on these units may have been intense enough to kill or more severely damage red maple stems, thereby contributing to a greater sprouting response (Masaka et al., 2000), but not severe enough to kill rootstocks or even the dormant buds that sprout from the base of trees. Waldrop and Lloyd (1991) found that annual winter burns allowed root systems to recover and to produce larger numbers of sprouts after each fire, while annual summer burns were better able to eradicate hardwood sprouts.

Stand manipulation to improve oak regeneration may require a combination of thinning, herbicide and fire, or alternatively, a somewhat different and longer-term approach to using prescribed fire than that used in this study. Successful oak regeneration has been promoted with the combined use of shelterwood harvest and fire or herbicide (Loftis, 1985; Loftis, 1990; Brose et al., 1999). The burns in this study were typically conducted in mid to late March, before bud swell. Burning later in the spring may have a greater impact on the sprouting response of fire-sensitive species, when sprouts have become physiologically active and belowground carbohydrate reserves would be lowest, thereby limiting resprouting capacity. If three late-winter prescribed burns result in higher numbers of oak stems, additional means might be necessary to produce the light environment conducive for these stems to move beyond seedling sizes and into the midstory. While the fires successfully reduced midstory stem densities, midstory densities began to recover within the timeframe of this study.

5. Conclusions

Working in similar stands in the Great Smoky Mountains National Park, Harmon (1984) found that reintroduction of fire may decrease red maple importance, but suggested that restoration of pre-suppression stand structure is a long-term process. Furthermore, interpreting pre-suppression fire regimes is extremely difficult, if not impossible (Harmon, 1984). In savannah systems, Peterson and Reich (2001) maintain that fire alone will not restore the savannah, but with other means of overstory reduction, fire may maintain the desired stand structure. Other studies in the central hardwoods (Franklin et al., 2003; Hutchinson et al., 2005) also suggest that fire alone usually has not restored oak forest structure or improved regeneration, at least in the short term in sites that have been subjected to long-term fire-exclusion.

The many ways fire affects stand structure makes using fire complicated. In this study, repeated fire successfully reduced densities of red maple and white pine, but the effects on oak regeneration were not as clear. Long-term results of burning alone may or may not support the goal of promoting oak regeneration through prescribed fire. Managers must carefully consider their specific management objectives before deciding how to use prescribed fire in eastern forests, as well as consider additional or alternative silvicultural methods for the promotion of oak stands.

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