Responses of hardwood advance regeneration to seasonal prescribed fires in oak-dominated shelterwood stands

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Abstract: Effects of seasonal prescribed fires of varying intensities on density, mortality, stem form, height, and height growth of hardwood advance regeneration were investigated. Three mixed-hardwood stands on productive upland sites were cut using a shelterwood technique, each forming a block of spring burn, summer burn, winter burn, and control treatments. Advance regeneration was inventoried from permanent plots before and after burning. Fires top-killed nearly all hardwood regeneration, forcing the rootstocks to sprout. Fire treatments reduced densities of all hardwood species relative to not burning, with spring and summer fires causing greater density reduction than winter burning. Among species, oak (*Quercus* spp. L.) and hickory (*Carya* spp. Nutt.) were more resilient sprouters than yellow-poplar (*Liriodendron tulipifera* L.) and red maple (*Acer rubrum* L.), especially as fire intensity increased. All prescribed fires improved oak stem form and stimulated height growth of hickory and oak. Overall, prescribed fires improved oak advance regeneration with spring burning providing the most benefit. This approach of following a shelterwood harvest with prescribed fire may be a viable method of regenerating oak-dominated stands on productive upland sites.

Résumé : Les effets du brûlage dirigé, effectué à différentes saisons et à des intensités variables, sur la densité, la mortalité, la forme de la tige, la hauteur et la croissance en hauteur de la régénération feuillue préétablie ont été investigués. Trois peuplements de feuillus mélangés établis sur des sites riches situés sur les plateaux furent coupés selon la technique de la coupe progressive. Chaque peuplement constituait un bloc de traitements qui incluaient des brûlages printanier, estival et hivernal ainsi qu'un témoin. La régénération préétablie a été inventoriée dans des parcelles permanentes avant et après le brûlage. Le feu a tué la cime de presque tous les semis de feuillus forçant leur système racinaire à drageonner. Le brûlage a réduit la densité de toutes les espèces feuillues comparativement à l'absence de brûlage. Les brûlages printanier ou estival ont causé une plus forte réduction que le brûlage hivernal. Parmi les espèces présentes, le chêne (*Quercus* spp. L.) et le caryer (*Carya* spp. Nutt.) avaient une meillleure capacité de drageonner que le tulipier de Virginie (*Liriodendron tulipifera* L.) et l'érable rouge (*Acer rubrum* L.), particulièrement lorsque l'intensité du feu augmentait. Dans tous les cas, le brûlage dirigé a amélioré la forme de la tige du chêne et a stimulé la croissance en hauteur du caryer et du chêne. Dans l'ensemble, le brûlage dirigé a amélioré la régénération préétablie du chêne et le brûlage effectué au printemps a procuré le plus d'avantages. Cette approche consistant à utiliser le brûlage dirigé après une coupe progressive pourrait s'avérer une méthode viable pour régénérer les peuplements dominés par le chêne sur les sites riches des plateaux.
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Introduction

Throughout the eastern hardwood forest of North America, regenerating oak (*Quercus* spp. L.) stands on productive sites is a major challenge for resource managers (Beck and Hooper 1986; Pallardy et al. 1988; Hix and Lorimer 1991; Abrams and Nowacki 1992). Generally, oak seedlings become established in such stands following plentiful acorn crops but soon lose apical dominance in the dense shade, resulting in crooked flat-topped stems with little height growth (Lorimer 1993; Lorimer et al. 1994). Without disturbance reducing the amount of shade, this oak reproduction gradually dies, giving way to more shade-tolerant species, i.e., American beech (*Fagus grandifolia* Ehrh.), red maple (*Acer rubrum* L.), and sugar maple (*Acer saccharum* Marsh.), which become well established in the understory and slowly replace dominant oaks in the overstory (McGee 1984; Abrams and Downs 1990).

The shelterwood system often is recommended to regenerate oak stands because it reduces the dense shade (Sander et al. 1983; Hannah 1987), allowing existing oak regeneration to develop size and mass in their root systems (Loftis 1990*a*; Deen et al. 1993), a prerequisite for rapid height growth upon release (Sander 1971, 1972). However, the initial cut often stimulates regeneration of fast-growing intolerant species, such as sweet birch (*Betula lenta* L.), sweetgum (*Liquidambar styraciflua* L.), and yellow-poplar (*Liriodendron tulipifera* L.) (Loftis 1983; Schuler and Miller 1995). Between release of existing shade-tolerant regeneration and establishment and rapid height growth of intolerant seedlings, oak reproduction rapidly becomes outnumbered and overtopped. These changes often are undesirable because of oak's many ecological and economic values. Controlling competition while improving stem form and encouraging height growth of oak regeneration is essential in maintaining oak stands on productive sites.

Often the shelterwood system needs additional measures to

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Table 1. Site and stand characteristics of three hardwood stands before the initial shelterwood harvest.

Characteristic	Dunnavant	Lake Road	Ward Farm
Size (ha)	17	20	14
Forest type*	WO/SO	WO/BO/NRO	WO/BO
Basal area (m^2/ha)	28	27.5	27.5
Site index (white oak_{50})	23	24	23
Soil texture	Sandy loam	Sandy loam	Sandy loam
Age (dominant oak)	100	90	90
Slope position	Upper half	Upper half	Upper half
Aspect	NE	E, SE	E
Mean slope (%)	7	7	5
Slope range (%)	0–20	0–20	0–5

*WO, white oak; SO, scarlet oak; BO, black oak; NRO, northern red oak.

give oak reproduction a competitive advantage. Loftis (1990*a*) and Lorimer et al.(1994) demonstrated the value of understory competition control with herbicides. Tree shelters and artificial regeneration with high-quality nursery stock help stimulate height growth of oak advance regeneration (Potter 1988; Bowersox 1993; Gordon et al. 1995). Hannah (1987) suggested that prescribed fire may also be an appropriate follow-up treatment to shelterwood harvesting but this combination has not yet been tested.

Prescribed burning of shelterwood stands mimics the partial cutting – surface fire disturbance regime that created many high-quality oak stands on productive sites (Carvell and Tryon 1961; Van Lear and Waldrop 1989; Abrams 1992). Fire in a shelterwood setting may select for oak because that species emphasizes root growth over shoot development. Oak's competitors, i.e., red maple and yellow-poplar, take the opposite approach (Kelty 1989; Kolb et al. 1990) and may be at a disadvantage in a situation of successive disturbances.

In this study, we monitored changes in density, height, height growth, mortality, and stem form of hardwood advance regeneration for two growing seasons after seasonal prescribed fires in oak-dominated shelterwood stands. We choose these seasons because winter burning is a traditional practice in the southeastern United States, spring is the natural fire season, and Keyser et al. (1996) successfully burned oak-dominated shelterwood stands during the summer with encouraging results. Our hypothesis is that all seasonal fires will reduce the density of less-desirable regeneration more than that of oak while improving oak stem form and height growth. This hypothesis was the basis for several previous fire–oak studies in undisturbed stands (Wendel and Smith 1986; Merritt and Pope 1991; Barnes and Van Lear 1998). However, it has never been tested in a shelterwood environment.

Methods

Study area

This study was conducted at the Horsepen Wildlife Management Area in the Piedmont Physiographic Province of central Virginia (37°30′N, 78°33′W). This area consists of broad gently rolling hills at elevations between 150 and 180 m above mean sea level. Mean annual precipitation for the area is 110 cm distributed evenly throughout the year. The average growing season is 190 days. Mean annual temperature for the area is 14°C with a January mean of 4°C and a July mean of 24°C (Reber 1988). The area is presently owned and managed by the Virginia Department of Game and Inland Fisheries (VDGIF).

Table 2. Basal areas (m^2/ha) of major tree species in oak-dominated stands before and after the initial shelterwood harvest.

Stand	Species	Before	Removed	After
Dunnavant	Hickory	2.0	0.2	1.8
	Oak	18.1	9.7	8.4
	Other*	6.4	6.0	0.4
	Yellow-poplar	1.5	0.6	0.9
	Total	28.0	16.5	11.5
Lake Road	Hickory	1.3	0.1	1.2
	Oak	21.0	9.2	11.8
	Other*	3.3	2.8	0.5
	Yellow-poplar	1.9	1.4	0.5
	Total	27.5	13.5	14.0
Ward Farm	Hickory	1.3	0.3	1.0
	Oak	17.8	6.9	10.9
	Other*	7.1	6.1	1.0
	Yellow-poplar	1.3	0.5	0.8
	Total	27.5	16.5	13.7

*Includes American beech, red maple, and sweetgum.

Three hardwood stands (Dunnavant, Lake Road, and Ward Farm), cut to a shelterwood 2–4 years earlier, were selected in 1994 for the study. According to VDGIF records, stands were similar in site and stand characteristics before the initial harvest (Table 1). Site index at age 50 years (site $index_{50}$) for oak averaged 23 m, and basal areas averaged nearly 28 m^2/ha. Soils were of the Cecil series, which are deep, well-drained sandy loams (Typic Hapludult) derived from gneiss, granite, and schist parent material (Reber 1988). Common overstory trees were white oak (*Quercus alba* L.), yellow-poplar, northern red oak (*Quercu rubra* L.), black oak (*Quercus velutina* Lam.), scarlet oak (*Quercus coccinea* Muenchh.), pignut hickory (*Carya glabra* (Mill.) Sweet), mockernut hickory (*Carya tomentosa* (Poiret) Nutt.), and chestnut oak (*Quercu prinus* L.). Ages of dominant oaks were determined by coring five trees per stand and ranged from 90 to 100 years. Common midstory hardwoods included red maple, flowering dogwood (*Cornus florida* L.), blackgum (*Nyssa sylvatica* Marsh.), American beech, and sourwood (*Oxydendrum arboreum* L.).

Harvesting removed most codominant and intermediate oaks and low-value species, leaving 50% of the canopy, because VDGIF wanted dominant oaks retained for acorn production (Table 2). Two stands were harvested in summer 1990 and the third in winter 1992. Slash was left in place. Volumes removed averaged 50 m^3/ha, and residual basal areas averaged 13 m^2/ha.

Study design and measurements

Density

A randomized complete block design was used to evaluate season-of-burn effects on advance regeneration. Each stand was divided into four 2- to 5-ha treatment areas (winter burn, spring burn, summer burn, and an unburned control), with 15 permanent 20-m^2 plots systematically located in each treatment. Preburn densities of hickory (pignut and mockernut), oak (white, northern red, black, scarlet, and chestnut), red maple, and yellow-poplar advance regeneration between 0.3 and 3.0 m tall were tallied in each plot in fall of 1994. Multiple stems arising from the same rootstock were counted as one stem. Postburn densities were tallied in fall of 1995 and 1996.

Mortality

Because fire intensity would vary among and within treatments, temperature and fuel consumption were measured in each plot during each prescribed burn. Temperature was measured by placing two

Table 3. Environmental conditions of seasonal prescribed fires in oak-dominated shelterwood stands.

Conditions	Dunnavant	Lake Road	Ward Farm
Winter burn			
Burn date	2/25/95	2/27/95	2/27/95
Time of burn	13:00	11:00	14:30
Air temperature (°C)	8	6	9
Relative humidity (%)	26	62	54
Wind direction	NW	E	E
Wind speed (km/h)	6	3	4
Cloud cover (%)	0	100	100
Fuel moisture (%)*	10	15	15
Spring burn			
Burn date	4/26/95	4/26/95	4/26/95
Time of burn	20:00	16:30	18:30
Air temperature (°C)	20	23	21
Relative humidity (%)	28	20	20
Wind direction	SW	SW	SW
Wind speed (km/h)	2	8	5
Cloud cover (%)	0	0	0
Fuel moisture (%)*	10	10	10
Summer burn			
Burn date	8/24/95	8/24/95	8/24/95
Time of burn	16:30	14:30	12:30
Air temperature (°C)	33	35	35
Relative humidity (%)	56	44	46
Wind direction	SW	SW	SW
Wind speed (km/h)	1	8	6
Cloud cover (%)	0	0	0
Fuel moisture (%)*	14	14	14

*Moisture of downed woody debris between 0.64 and 2.54 cm diameter.

ceramic tiles marked with heat-sensitive paints (40–260°C in 20°C increments) on the outer edge of each plot, opposite from each other, at 1 m height, and facing towards plot center. Depending on fire intensity, some of the paints melted as the fire passed through the plot, providing an estimate of the maximum heat produced in each plot. Fuel consumption was estimated by photographing each plot before burning, then comparing postburn appearance immediately after the fires to the preburn photograph.

After burning, each plot was placed into one of four fire intensity categories based on average fire temperature and fuel consumption. Low fire intensity was characterized by partial combustion of fine fuels (litter and woody debris <0.6 cm diameter), average temperatures <65°C, and less than 75% top kill of advance regeneration. Medium–low fire intensity had complete burning of fine fuels, average temperatures of 65–135°C, and 75–100% top kill of regeneration. Medium–high fire intensity had reduction of 2.5–7.5 cm diameter fuels, average temperatures between 135 and 200°C, some midstory tree mortality, bark scorch on overstory trees, and 100% top kill of regeneration. High fire intensity was indicated by partial consumption of woody debris >7.5 cm diameter, average temperatures exceeding 200°C, frequent midstory mortality, and occasional overstory mortality. Assignment of plots to different fire intensity levels resulted in sample sizes of 10–15 plots per level.

Assignment of plots to different fire intensity levels after burning created a 3 × 4 factorial design with three fire seasons and four fire intensity levels. This factorial tested the effect of varying fire intensity within and among season of burn on mortality of each species. Mortality percent was defined as the number of stems of a species failing to sprout by the end of the first postburn growing season divided by total number of stems of that species in each plot prior to burning.

Table 4. Behavior of seasonal prescribed fires in oak-dominated shelterwood stands.

Conditions	Dunnavant	Lake Road	Ward Farm
Winter burn			
Flame length (m)	0.7	0.2	0.4
Rate of spread (m/min)	1.4	0.4	0.4
Spring burn			
Flame length (m)	0.6	1.3	0.8
Rate of spread (m/min)	0.6	2.5	0.8
Summer burn			
Flame length (m)	0.2	0.8	0.8
Rate of spread (m/min)	0.2	1.5	1.2

Height, height growth, and form

In each treatment area, six stems each of white oak, northern red oak, black oak, scarlet oak, red maple, yellow-poplar, and hickory (mockernut and pignut) were chosen and permanently marked with metal tags. These stems were representative of the observed average height of surrounding advance regeneration. All marked advance regeneration were true seedlings or seedling sprouts (Johnson 1993). Stump sprouts were not included.

Each stem was measured for total height, height growth during 1994, and root collar diameter. To evaluate stem quality, all oak stems were also rated for form as straight strong leader, flat topped with no dominant leader, and intermediate (Loftis 1990*b*). Preburn measurements and ratings were made in fall 1994. Postburn measurements and ratings were made in fall 1995 and 1996 for control, spring-burn, and winter-burn treatments and in fall 1996 and 1997 for summer-burn treatment.

Prescribed fires

Prescribed fires were conducted on February 25 and 27 (winter burn), April 26 (spring burn), and August 24 (summer burn), 1995, by VDGIF personnel in accordance with department policy and state law. The spring fires occurred when leaves were 50–75% expanded. Fuel and weather conditions varied among and within seasons (Table 3). All prescribed fires were ignited by hand with drip torches in a strip-head fire pattern commencing at the downwind side of the treatment. Ignition strips were initially spaced 3 m apart and gradually widened to 15 m once firelines were secured.

Spring fires produced the most intense fire behavior with flame lengths and rates-of-spread averaging 0.8 m and 1.3 m/min, respectively (Table 4). Winter and summer fires behaved similarly to spring fires when weather conditions permitted but increases in relative humidity and decreases in wind resulted in lower intensity fires. Overall, prescribed burns were easily executed.

Statistical analysis

Analysis of covariance with Student–Newman–Kuels mean separation test was used to compare season-of-burn treatments for decreases in stem density and changes in height growth (SAS Institute Inc. 1993). Covariates for density analysis were preburn density, time since harvest, and fire temperature while height growth covariates were preburn root collar diameter, height growth, and total height. Differences in oak stem form among fire seasons and between preburn and postburn were tested using chi-square analysis (SAS Institute Inc. 1993). Analysis of variance with Student–Newman–Kuels mean separation test was used to evaluate differences in density and total height among species before and after the prescribed fires (SAS Institute Inc. 1993). Changes in density and total height between preburn and postburn were tested using paired *t* tests (SAS Institute Inc. 1993). Analysis of variance with least square mean separation was used to test for differences among species mortality as fire intensity interacted with season of burn (SAS Institute Inc. 1993). In all tests,

Table 5. Preburn characteristics (mean ± SE) of advance regeneration in shelterwood stands.

Species	Density (stems/ha)	Total height (cm)	Height growth (cm/year)	Root collar diameter (mm)
Control				
Hickory	1877±210*b*	87±9*b*	18±4*b*	17±2*a*
Oak	1578±163*b*	83±3*b*	17±1*b*	19±1*a*
Red maple	4478±699*a*	108±10*a*	35±4*a*	21±2*a*
Yellow-poplar	5572±996*a*	120±10*a*	38±3*a*	20±1*a*
Winter burn				
Hickory	1811±247*c*	125±8*b*	27±3*b*	29±2*a*
Oak	1771±185*c*	118±9*b*	27±2*b*	31±2*a*
Red maple	3800±306*b*	190±16*a*	48±2*a*	35±4*a*
Yellow-poplar	7311±973*a*	204±19*a*	49±4*a*	32±4*a*
Spring burn				
Hickory	2267±240*b*	110±9*b*	30±4*b*	25±3*a*
Oak	2376±263*b*	117±9*b*	26±3*b*	27±2*a*
Red maple	4463±415*a*	163±11*a*	47±3*a*	24±4*a*
Yellow-poplar	5901±800*a*	155±14*a*	43±2*a*	24+3*a*
Summer burn				
Hickory	1934±215*c*	74±9*b*	16±2*b*	19±1*a*
Oak	3038±543*b*	86±5*b*	19±2*b*	21±1*a*
Red maple	3144±484*b*	155±13*a*	34±3*a*	23±4*a*
Yellow-poplar	9957±962*a*	160±8*a*	35±2*a*	20±2*a*

Note: Means within a treatment and column followed by different letters are significantly different (α = 0.05).

Table 6. Adjusted declines in stem density and changes in height growth (mean ± SE) for two growing seasons (GS) after seasonal prescribed fires in shelterwood stands.

		Height growth	
Treatment	Density (stems/ha)	First GS (cm/year)	Second GS (cm/year)
Hickory			
Control	76±8*e*	19±3*f*	18±5*d*
Winter burn	643±55*d*	52±3*d*	61±4*a*
Spring burn	662±50*d*	39±3*e*	58±4*a*
Summer burn	1105±62*c*	31±5*e*	31±5*c*
Oak			
Control	79±7*e*	17±2*f*	22±2*d*
Winter burn	531±48*d*	71±4*c*	48±3*b*
Spring burn	543±64*d*	57±3*d*	40±3*c*
Summer burn	1124±78*c*	40±5*e*	36±3*c*
Red maple			
Control	82±6*e*	34±4*e*	44±4*b*
Winter burn	541±71*d*	140±14*a*	43±4*b*
Spring burn	1425±181*c*	94±9b	44±6*b*
Summer burn	1475±158*c*	60±5*c*	30±4*c*
Yellow-poplar			
Control	70±8*e*	40±5*e*	50±3*b*
Winter burn	2801±197*b*	137±12*a*	47±6*b*
Spring burn	4169±335*a*	101±17*b*	48±9*b*
Summer burn	4231±387*a*	51±9*de*	32±4c

Note: Means within a column followed by different letters are significantly different (α = 0.05).

α was 0.05 and data were arcsine or rank transformed as needed to correct unequal variances and non-normality of residual values.

Results

Although designed as a randomized complete block study, no differences in density, mortality, form, height growth, or total height of advance regeneration were detected among stands before the prescribed fires. Likewise, changes in these variables after burning were consistent in direction and magnitude among stands. Therefore, data were pooled to simplify reporting. Also, no differences in form, height, height growth, and root collar diameter were found among the four oak species (white, northern red, black, and scarlet) before or after treatment, so their data were pooled to simplify reporting.

Preburn conditions

In 1994, yellow-poplar was the most abundant, fastest growing, and tallest species in all treatments (Table 5). Red maple was as tall and fast growing as yellow-poplar but not as plentiful. Hickory and oak reproduction were present but not to the extent of their competitors and were shorter and growing slower than red maple and yellow-poplar. Only a small percentage of oak stems were straight. No differences in root collar diameter were detected among species in any of the treatments.

Density

Initial analysis of potential covariates revealed that time since harvest was not a significant factor. The 2-year-old shelterwood stand suffered ice storm damage several years before the initial harvest. The reduction in overstory shade probably stimulated development of existing oak regeneration sufficient to offset the time-since-harvest difference among the stands.

After adjusting for preexisting differences in stem density and variation in fire temperature among and within season of burn, all fire treatments reduced densities of all species relative to not burning (Table 6). Spring and summer fires reduced densities of red maple and yellow-poplar more than winter burning. For hickory and oak, summer burning caused the largest decrease in stem density with no difference detected between spring and winter burning. Among species, all fire treatments decreased yellow-poplar density more than that of any other species. No differences were detected among any species in the control nor between hickory and oak in any fire treatment. Oak and red maple differed only in the spring burn treatment with red maple density reduction exceeding that of oak by nearly 1000 stems/ha.

Height growth

During the first growing season after prescribed burning (1996 for control, winter burn, and spring burn; 1997 for summer burn), all species grew most in the winter burn treatment and least in the control treatment (Table 6). Growth for all species following spring and summer fire was intermediate, greater than the control but less than after winter burning. In all treatments, yellow-poplar and red maple grew fastest, while hickory grew slowest. Oak and hickory grew at similar rates in the control, but oak grew slightly faster than hickory in the fire treatments.

Table 7. Percent mortality (mean ± SE) of advance regeneration in four different levels of fire intensity.

	Fire intensity			
Species	Low	Medium–low	Medium–high	High
	Winter burn			
Hickory	15±7*a,y*	13±9*a,z*	18±9*a,z*	15±4*a,z*
Oak	16±7*a,y*	14±7*a,z*	17±7*a,z*	20±9*a,z*
Red maple	13±7*c,y*	30±9*b,yz*	34±9*b,yz*	67±4*a,x*
Yellow-poplar	54±8*b,w*	78±9*a,w*	74±11*a,w*	76±6*a,w*
	Spring burn			
Hickory	9±5*b,y*	19±9*b,z*	14±9*b,z*	37±11*a,y*
Oak	10±9*a,y*	16±7*a,z*	16±7*a,z*	26±7*a,y*
Red maple	23±8*c,xy*	34±9*c,y*	52±9*b,x*	74±9*a,wx*
Yellow-poplar	68±13*b,w*	82±9*a,w*	90±9*a,w*	92±9*a,w*
	Summer burn			
Hickory	10±3*b,y*	18±5*b,z*	33±9*a,y*	47±9*a,x*
Oak	23±3*b,x*	44±6*a,xy*	53±7*a,x*	55±9*a,x*
Red maple	41±8*a,w*	52±5*a,x*	52±6*a,x*	69±9*a,x*
Yellow-poplar	70±9*b,w*	81±5*a,w*	80±10*a,w*	89±9*a,w*

Note: Means followed by different letters are significantly different (*a*–*c*, within species rows; *w*–*z*, within fire intensity columns; $\alpha = 0.05$). n = 10–15 for each season of burn × intensity combination.

Table 8. Proportion of oak regeneration (mean ± SE) in each stem form class before, one, and two growing seasons (GS) after seasonal prescribed fires in shelterwood stands.

Treatment	Stem form class	Before	1st GS	2nd GS
Control	Flat topped	66*a,v*	66*a,v*	67*a,w*
	Intermediate	21*a,w*	21*a,w*	26*a,x*
	Straight	13*a,x*	13*a,x*	7*b,z*
Winter burn	Flat topped	61*a,v*	3*b,y*	0*b,z*
	Intermediate	29*a,w*	10*b,x*	38*a,x*
	Straight	10*c,x*	87*a,v*	62*b,vw*
Spring burn	Flat topped	66*a,v*	4*b,y*	2*b,z*
	Intermediate	24*b,w*	12*c,x*	41*a,w*
	Straight	10*c,x*	84*a,v*	57*b,w*
Summer burn	Flat topped	66*a,v*	2*b,z*	5*b,z*
	Intermediate	23*a,w*	15*a,y*	20*a,y*
	Straight	11*b,x*	83*a,v*	77*a,v*

Note: Percentages followed by different letters are significantly different (*a*–*c*, within rows; *v*–*z*, within columns; $\alpha = 0.05$).

Height growth for all species decreased in all fire treatments during the second growing season (1996 for control, winter burn, and spring burn; 1997 for summer burn) relative to the first postburn growing season (Table 6). Red maple and yellow-poplar growth in the spring and winter treatments became equal to that of the control and growth in the summer treatment was less than that of the control. Hickory and oak growth also slowed in all fire treatments but remained accelerated relative to the control.

Among treatments, hickory grew fastest in the winter and spring fire treatments, intermediate in the summer fire treatment, and slowest in the control. Oak was similar to hickory with second-year growth being the fastest in the winter burn, intermediate in the spring and summer fire treatments, and slowest in the control. Red maple and yellow-poplar grew slowest in the summer fire treatment and were equal in all other treatments.

Among species, hickory grew fastest in the spring and winter fire treatments, red maple and yellow-poplar grew fastest in the control, and there were no differences detected among species growth rates in the summer burn treatment.

Mortality

Mortality trends among species were consistent as fire intensity interacted with season-of-burn (Table 7). Generally, mortality rates were least for all species at the low intensity level in the winter burn treatment and rose as fire intensity increased and (or) season changed from winter to spring to summer. However, the rate of change in species mortality rates differed among species. Yellow-poplar mortality ranged from 54 to 92%, depending on season and intensity, and was always greater than that of hickory and oak mortality. Red maple mortality ranged from 13 to 74% and differed from that of hickory and oak at the highest winter fire intensity, medium low to high spring fire intensity, and the lowest summer fire intensity. Hickory and oak mortality rates stayed the same in the winter and spring fire treatments, but oak mortality exceeded hickory mortality in all but the highest summer fire intensity.

Stem form

Prior to burning, about 89% of all oak reproduction had crooked or flat-topped stems (Table 8). During the first growing season after prescribed burning, oak stem form improved in all treatments except the control. Among fire treatments, 83–87% of the stems were straight, 10–15% were intermediate, and 2–4% were flat topped with no differences found among treatments.

During the second growing season after prescribed burning, all fire treatments continued having a larger proportion of straight stems than the control (Table 8). However, a decline in stem form from straight to intermediate occurred in the control, spring burn, and winter burn treatments relative to the preceding year. This decline was probably not related to the treatments but was caused by a massive outbreak of 17-year cicadas (*Magicicada septendecim* L.) during summer 1996. The cicadas oviposited on nearly every stem large enough to accommodate them, causing deformation and dieback. Apparently sprouts in the summer burn treatment were too small to serve as ovipositing sites.

Postburn conditions

Two years after the prescribed fires, there were noticeable differences among the treatments (Table 9). In the control treatment, yellow-poplar was the most common, fastest growing, and tallest species. Red maple continued as the second most abundant species and equaled yellow-poplar in height and height growth. Hickory and oak remained outnumbered, shorter, and slower growing than their competitors with most oak stems being flat topped. However, in the fire treatments, oak density increased in the spring and winter fire treatments relative to before burning, becoming equal to or greater than red maple and yellow-poplar densities. This increase was caused by oak reproduction too small to be included in the initial inventory (<0.3 m tall) sprouting and vigorously growing into the sampling strata. Red maple and yellow-poplar

Table 9. Density and height (mean ± SE) of advance regeneration 2 years after seasonal prescribed fires.

Species	Density (stems/ha)	Height (cm)
Control		
Hickory	1645±235*c*	110±9*c*
Oak	1428±254*c*	105±6*c*
Red maple	4411±504*ab*	156±10*b**
Yellow-poplar	5555±911*a*	213±13*a**
Winter burn		
Hickory	1988±347*c*	112±6*c*
Oak	2957±168*b**	113±6*c*
Red maple	2811±311*b***	180±17*b*
Yellow-poplar	3216±469*b***	207±20*ab*
Spring burn		
Hickory	2090±217*c*	98±8*c***
Oak	3367±516*b**	91±5*c***
Red maple	2455±415*b***	152±8*b*
Yellow-poplar	2097±442*b***	170±27*b*
Summer burn		
Hickory	1338±230*c***	62±9*f***
Oak	2880±380*b*	70±5*ef***
Red maple	1690±257*c***	87±7*d***
Yellow-poplar	2724±600*b***	85±9*de***

Note: Means followed by different letters are significantly different within that column ($\alpha = 0.05$).

*Significant increase from the corresponding preburn mean given in Table 5 ($\alpha = 0.05$).

**Significant decrease from the corresponding preburn mean given in Table 5 ($\alpha = 0.05$).

continued as the tallest species, but oak and hickory were growing as fast as their competitors and oak reproduction had improved stem form.

Discussion

This study demonstrates that hickory and oak reproduction are more resistant than red maple and yellow-poplar regeneration to prescribed fires if burning occurs several years after an initial shelterwood harvest. However, not all fires are equal. Medium- to high-intensity fires during the spring and summer reduced red maple and yellow-poplar density more than low-intensity winter burns. Hickory and oak density were largely unaffected by winter and spring fires and less impacted by summer fires than red maple and yellow-poplar. As a result of these mortality differences, oaks were just as numerous or more numerous than their competitors 2 years after the fire treatments, especially where high fire intensity and spring or summer burning combined to nearly eliminate the competition. Differences in mortality rates among species are probably due to different germination and growth strategies.

Acorns and hickory nuts are frequently buried by wildlife (Darley and Johnson 1981; Galford et al. 1989) whereas seeds from red maple and yellow-poplar are probably not cached to the same degree. Differences among species in seed burial by wildlife is accentuated by germination strategy. Hickory and oak have hypogeal germination (cotyledons remain in the seed), causing the root collar and its accompanying dormant buds to be below the soil surface (Rogers 1990; Sander 1990; Smalley 1990; Smith 1990). Red maple and yellow-poplar have epigeal germination (cotyledons emerge from seed), placing the root collar at or above the soil surface (Beck 1990; Walters and Yawney 1990). A seedling whose root collar and dormant buds are below ground level will be more likely to survive a surface fire than a seedling whose root collar and dormant buds are at or above ground level.

Hickory and oak also have different growth strategies than red maple and yellow-poplar. The former emphasize root development in lieu of shoot growth in their early years while the latter take the opposite approach (Kelty 1989; Kolb et al. 1990). As a result, hickory and oak generally have larger roots than comparably sized red maple and yellow-poplar (Barnes and Van Lear 1998). While not formally examined in this study, random extraction of rootstocks from the treatment areas suggested that oak had larger roots than comparable red maple and yellow-poplar.

Oak reproduction that sprouts after a fire exhibits improved stem form and height growth relative to not being burned. Besides contributing to oak's superior fire resistance, the large roots probably account for the improvement in oak stem form after the fire treatments. When fires killed existing stems, oak rootstocks generally sent up a single vigorous sprout. The results were straight sprouts replacing crooked stems (Fig. 1). Improved oak stem form is important because new sprouts are well anchored, free from rot, and have a greater probability of becoming sound timber trees (Roth and Hepting 1943; Teuke and Van Lear 1982).

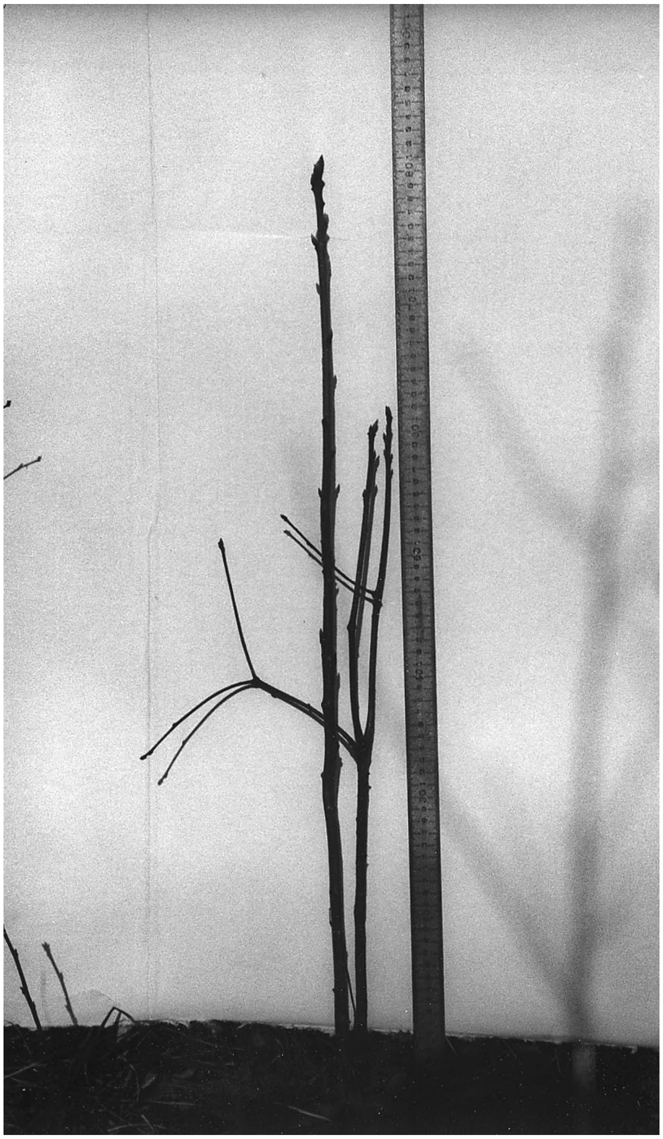
Acceleration of hickory and oak height growth was also probably a result of their large roots. Hickory and oak advance regeneration showed accelerated height growth for at least 2 years following winter and spring fire. The new oak stems should maintain height growth rates of 50–100 cm/year for several years (Waldrop 1997) helping them gain a stronger competitive position in the new stand. Conversely, red maple and yellow-poplar accelerated height growth for only 1 year before returning to preburn rates.

These differences in germination and growth strategies between oak and its competitors benefit oak in a combined disturbance regime of moderate canopy openings followed by fire. Such a disturbance regime once existed in many parts of the eastern hardwood forest of North America (Pyne 1982).

Historically, natural disturbances such as insect outbreaks, ice storms, passenger pigeon activity, or wind events created moderate canopy openings (Lorimer 1980; Runkle 1990). Such disturbances predisposed the forest to fire by elevating fuel loadings, facilitating air movement, and increasing sunlight (Myers and Van Lear 1998). The increase in sunlight is especially important, because dense shade hinders oak regeneration development (Lorimer et al. 1994). A shelterwood harvest mimics moderate canopy disturbances and releases oak reproduction to develop their root systems.

The role of fire as an important disturbance in mixed hardwood forests is beginning to be understood and appreciated. Native Americans frequently used fire to manipulate their environment for numerous reasons (Pyne 1982; Denevan 1992), and some fires certainly occurred in stands previously impacted by moderate canopy disturbances. Settlers adopted many of these burning practices and made repeated partial

Fig. 1. A straight vigorous oak sprout (left) replaces a poorly formed stem (right) top-killed by prescribed burning.

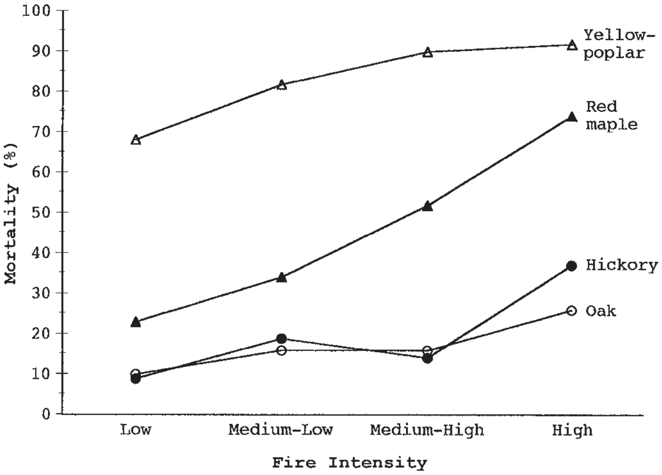


harvests, many of which were followed by fire (Pyne 1982; Van Lear and Waldrop 1989; Abrams 1992). The combination of these disturbances probably played a substantial role in creating and maintaining oak-dominated stands on productive upland sites.

Fire suppression policies of the past 50–75 years disrupted this disturbance regime, contributing to fire-sensitive species successfully outcompeting oak regeneration on productive upland sites (Pyne 1982). Combining prescribed fire with shelterwood harvesting would return mixed-hardwood forests to a natural disturbance regime and may help solve the oak regeneration problem.

Restoration of this combined disturbance regime must take into account the timing between events. The time interval of several years between harvest and burning may be critical, allowing oak the time required to develop relatively large root systems (Kelty 1989; Kolb et al. 1990). If the fires occur before or immediately after the harvest, oak mortality may be substantial (Johnson 1974; Wendel and Smith 1986). The time interval also permits yellow-poplar seed stored in the forest floor to germinate, becoming vulnerable to surface fires. Shearin et al. (1972) showed that many yellow-poplar seeds survive fires, but seedlings have little defense (Barnes and Van Lear 1998). The partial shade also slows their height growth (Clark 1968; Beck 1990) keeping them vulnerable to fires.

Fig. 2. Mortality (%) of hickory, oak, red maple, and yellow-poplar advance regeneration as fire intensity increases within spring prescribed burns conducted in shelterwood stands.



Season-of-burn differences in species mortality and height growth are probably because rootstocks have full carbohydrate reserves at the time of winter burning and diminished root carbohydrate reserves during spring and summer fires (Hodgkins 1958; Ferguson 1961). Full carbohydrate reserves help rootstocks withstand fall and winter fires and grow rapidly afterwards. Rootstock survival and height growth are lessened when fires occur during the growing season because root carbohydrate reserves are low (Hodgkins 1958; Langdon 1981).

Spring burning during leaf expansion appears to offer the best blend of benefits when burning for oak regeneration. It significantly reduced densities of red maple and yellow-poplar at medium to high intensities with minimal losses of oak even at high intensities (Fig. 2). While height growth was not as fast as after winter burning, it was still a substantial improvement over not burning. Improvement of stem form was comparable with other fire treatments. Favorable weather (warm temperatures, low humidities, sunny days, and southerly winds) create numerous burning opportunities. However, these weather conditions can also increase the likelihood of a fire escape and may contribute to more overstory tree mortality (Rouse 1986).

Summer fire produces results comparable with spring fire but presents fewer burning opportunities as steady winds of 5–10 km/h are needed to offset higher humidities and partial shade. Likewise, fall and winter burning may also be inhibited by marginal burning conditions such as cooler ambient temperatures and low insolation levels. Marginal burning conditions coupled with full root carbohydrate reserves mean that several winter fires are needed to have the same impact as a single growing-season fire (Barnes and Van Lear 1998).

Whether the reduction in density of competitors, improvement in oak stem form, and stimulation of oak height growth are enough to produce oak-dominated stands on these productive sites in the future is unclear. Red maple and yellow-poplar are still common and vigorously growing. However, their distribution is now patchy, being most common in areas that received low intensity fire during the winter and fewest where high intensity fire occurred during the growing season. Single intense fires have occasionally created oak-dominated stands under some conditions (Brown 1960; Carvell and Maxey 1969; Ward and Stephens 1989). For some reason, intense competition control can sometimes stimulate rapid growth in oak reproduction, allowing it to dominate the regeneration pool (Johnson et al. 1989; Lorimer 1989). Depending on development of the regeneration during the stand initiation phase, additional fires may be needed to ensure oak domination. Regardless of whether single or multiple fires are needed, prescribed burning after a shelterwood harvest is a promising approach to regenerating oak stands on productive sites.

More research of the fire–oak relationship is warranted to answer questions arising from this study. Testing of this method in other physiographic regions and forest types of North America is needed. Is sprouting after a fire a function of root size alone or are there other factors, such as location and number of adventitious buds? What are the implications of this approach to understory plants and wildlife species? Will the short-term benefits shown in this study ensure long-term success? Prescribed fire appears to have a place in oak management and answering the above questions, as well as others, will provide guidance for resource managers seeking to maintain oaks on productive sites.

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References

Abrams, M.D. 1992. Fire and the development of oak forests. BioScience, **42**: 346–353.

Abrams, M.D., and Downs, J.A. 1990. Successional replacement of old-growth white oak by mixed mesophytic hardwoods in southwestern Pennsylvania. Can. J. For. Res. **20**: 1864–1870.

Abrams, M.D., and Nowacki, G.J. 1992. Historical variation in fire, oak recruitment, and post-logging accelerated succession in central Pennsylvania. Bull. Torrey Bot. Club, **119**: 19–28.

Barnes, T.A., and Van Lear, D.H. 1998. Prescribed fire effects on hardwood advance regeneration in mixed hardwood stands. South. J. Appl. For. In press.

Beck, D.E. 1990. Yellow-poplar. *In* Silvics of North America. Vol. 2. Hardwoods. *Compiled by* R.M. Burns and B.H. Honkala. U.S. Dep. Agric. Agric. Handb. 654. pp. 406–416.

Beck, D.E., and Hooper, R.M. 1986. Development of a Southern Appalachian hardwood stand after clearcutting. South. J. Appl. For. **10**: 168–172.

Bowersox, T.W. 1993. Artificial regeneration of oaks in the uplands. *In* Proceedings, Oak Regeneration: Serious Problems, Practical Recommendations, 8–10 Sept. 1992, Knoxville, Tenn. *Edited by* D. Loftis and C. McGee. USDA For. Serv. Gen. Tech. Rep. SE-84. pp. 250–263.

Brown, J.H. 1960. The role of fire in altering the species composition of forests in Rhode Island. Ecology, **41**: 310–316.

Carvell, K.L., and Maxey, W.R. 1969. Wildfire destroys! W.Va. Agric. For. Exp. Stn. Bull. 2. pp. 4–5, 12.

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

Clark, F.B. 1968. The silviculture of oak and associated species. USDA For. Serv. Res. Pap. NE-144.

Darley, H., and Johnson, P.S. 1981. Acorn disposal by the blue jay (*Cyanocitta cristata*). Oecologia, **50**: 231–232.

Deen, R.T., Hodges, J.D., and Janzen, G.C. 1993. The influence of midstory–understory control treatments on regeneration of redoak species following clearcutting. *In* Proceedings of the 7th Biennial Southern Silvicultural Research Conference, 17–19 Nov. 1992, Mobile, Ala. *Edited by* J. Brissette. USDA For. Serv. Gen. Tech. Rep. SO-93. pp. 117–121.

Denevan, W.M. 1992. The pristine myth: the landscape of the Americas in 1492. Ann. Assoc. Am. Geogr. **82**: 369–385.

Ferguson, E.R. 1961. Effects of prescribed fires on understory stems in pine–hardwood stands in east Texas. J. For. **59**: 356–359.

Galford, J.R., Peacock, J.W., and Wright, S.L. 1989. Insects and other pests affecting oak regeneration. *In* Proceedings, Guidelines for Regenerating Appalachian Hardwood Stands, 24–26 May 1989. Morgantown, W.Va. *Edited by* H.C. Smith, A.W. Perkey, and E. William. West Virginia University, Morgantown, W.Va. pp. 219–225.

Gordon, A.M., Simpson, J.A., and Williams, P.A. 1995. Six-year response of red oak seedlings planted under a shelterwood in central Ontario. Can. J. For. Res. **25**: 603–613.

Hannah, P.R. 1987. Regeneration methods for oaks. North. J. Appl. For. **4**: 97–101.

Hix, D.M., and Lorimer, C.G. 1991. Early stand development on former oak sites in southwestern Wisconsin. For. Ecol. Manag. **42**: 169–193.

Hodgkins, E.J. 1958. Effect of fire on undergrowth vegetation in upland southern pine forests. Ecology, **39**: 36–46.

Johnson, P.S. 1974. Survival and growth of northern red oak seedlings following a prescribed burn. USDA For. Serv. Res. Note NC-177.

Johnson, P.S. 1993. Sources of oak reproduction. *In* Proceedings, Oak Regeneration: Serious Problems, Practical Recommendations, 8–10 Sept. 1992, Knoxville, Tenn. *Edited by* D. Loftis and C. McGee. USDA For. Serv. Gen. Tech. Rep. SE-84. pp. 112–133.

Johnson, P.S., Jacobs, R.D., Martin, A.J., and Godel, E.D. 1989. Regenerating northern red oak: three successful case studies. North. J. Appl. For. **6**: 174–178.

Kelty, M.J. 1989. Sources of hardwood regeneration and factors that influence these sources. *In* Proceedings, Guidelines for Regenerating Appalachian Hardwood Stands, 24–26 May 1989. Morgantown, W.Va. *Edited by* H.C. Smith, A.W. Perkey, and E. William. Office of Publications, West Virginia University, Morgantown, W.Va. pp. 17–30.

Keyser, P.D., Brose, P.H., Van Lear, D.H., and Burtner, K.M. 1996. Enhancing oak regeneration with fire in shelterwood stands: preliminary trials. Trans. N.Am. Wildl. Nat. Res. Conf. **61**: 215–219.

Kolb, T.E., Steiner, K.C., McCormick, L.H., and Bowersox, T.W. 1990. Growth response of northern red oak and yellow-poplar seedlings to light, soil moisture, and nutrients in relation to ecological strategy. For. Ecol. Manag. **38**: 65–78.

Langdon, O.G. 1981. Some effects of prescribed fire on understory vegetation in loblolly pine stands. *In* Proceedings, Prescribed Fire and Wildlife in Southern Forests, 6–8 Apr. 1981, Georgetown, S.C. *Edited by* G.W. Wood. Clemson University, Clemson, S.C. pp. 143–153.

Loftis, D.L. 1983. Regenerating Southern Appalachian mixed hardwood stands with the shelterwood method. South. J. Appl. For. **7**: 212–217.

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

Loftis, D.L. 1990*b*. Predicting post-harvest performance of advance red oak reproduction in the southern Appalachians. For. Sci. **36**: 908–916.

Lorimer, C.G. 1980. Age structure and disturbance history of a southern Appalachian virgin forest. Ecology, **61**: 1169–1184.

Lorimer, C.G. 1989. The oak regeneration problem: new evidence on causes and possible solutions. For. Res. Bull. 8. University of Wisconsin, Madison.

Lorimer, C.G. 1993. Causes of the oak regeneration problem. *In* Proceedings, Oak Regeneration: Serious Problems, Practical Recommendations, 8–10 Sept. 1992, Knoxville, Tenn. *Edited* by D. Loftis and C. McGee. USDA For. Serv. Gen. Tech. Rep. SE-84. pp. 14–39.

Lorimer, C.G., Chapman, J.W., and Lambert, W.D. 1994. Tall understory vegetation as a factor in the poor development of oak seedlings beneath mature stands. J. Ecol. **82**: 227–237.

McGee, C.E. 1984. Heavy mortality and succession in a virgin mixed mesophytic forest. USDA For. Serv. Res. Pap. SO-209.

Merritt, C., and Pope, P.E. 1991. The effect of environmental factors, including wildfire and prescribed burning, on the regeneration of oaks in Indiana. Purdue Univ. Dep. For. Nat. Res. Stn. Bull. 612.

Myers, R.K., and Van Lear, D.H. 1998. Hurricane–fire interactions in coastal forests of the South: a review and hypothesis. For. Ecol. Manag. In press.

Pallardy, S.G., Nigh, T.A., and Garrett, H.E. 1988. Changes in forest composition in central Missouri: 1968–1982. Am. Midl. Nat. **120**: 380–390.

Potter, M.J. 1988. Treeshelters improve survival and increase early growth rates. J. For. **86**: 39–41.

Pyne, S. 1982. Fire in America. Princeton University Press, Princeton, N.J.

Reber, E.J. 1988. Soil survey of Powhatan County, Virginia. USDA Soil Conservation Service, Washington, D.C.

Rogers, R.. 1990. White oak. *In* Silvics of North America. Vol. 2. Hardwoods. *Compiled by* R.M. Burns and B.H. Honkala. U.S. Dep. Agric. Agric Handb. 654. pp. 605–613.

Roth, E.R., and Hepting, G.H. 1943. Origin and development of oak stump sprouts as affecting their likelihood to decay. J. For. **41**: 27–36.

Rouse, C. 1986. Fire effects in northeastern forests: oak. USDA For. Serv. Gen. Tech. Rep. NC-105.

Runkle, J.R. 1990. Gap dynamics in an Ohio *Acer–Fagus* forest and speculations on the geography of disturbance. Can. J. For. Res. **20**: 632–641.

Sander, I.L. 1971. Height growth of new oak sprouts depends on size of advance reproduction. J. For. **69**: 809–811.

Sander, I.L. 1972. Size of oak advance reproduction: key to growth following harvest cutting. USDA For. Serv. Res. Pap. NC-79.

Sander, I.L. 1990. Northern red oak. *In* Silvics of North America. Vol. 2. Hardwoods. *Compiled by* R.M. Burns and B.H. Honkala. U.S. Dep. Agric. Agric. Handb. 654. pp. 727–733.

Sander, I.L., McGee, C.E., Day, K.G., and Willard, R.E. 1983. Oak–hickory. *In* Silvicultural systems of the major forest types of the United States. *Compiled by* R.M. Burns. U.S. Dep. Agric. Agric. Handb. 445. pp. 116–120.

SAS Institute Inc. 1993. SAS user's guide: statistics, version 6 edition. SAS Institute Inc., Cary, N.C.

Schuler, T.M., and Miller, G.W. 1995. Shelterwood treatments fail to establish oak reproduction on mesic forest sites in West Virginia—10 year results. *In* Proceedings of the 10th Central Hardwood Forest Conference, 5–8 Mar. 1995, Morgantown, W.Va. *Edited by* K.W. Gottschalk and S.L. Fosbroke. USDA For. Serv. Gen. Tech. Rep. NE-197. pp. 375–386.

Shearin, A.T., Bruner, M.H., and Goebel, N.B. 1972. Prescribed burning stimulates natural regeneration of yellow-poplar. J. For. **70**: 482–484.

Smalley, G.W. 1990. Pignut hickory. *In* Silvics of North America. Vol. 2. Hardwoods. *Compiled by* R.M. Burns and B.H. Honkala. U.S. Dep. Agric. Agric. Handb. 654. pp. 198–204.

Smith, H.C. 1990. Mockernut hickory. *In* Silvics of North America. Vol. 2. Hardwoods. *Compiled by* R.M. Burns and B.H. Honkala. U.S. Dep. Agric. Agric Handb. 654. pp. 226–233.

Teuke, M.J., and Van Lear, D.H. 1982. Prescribed burning and oak advance regeneration in the southern Appalachians. Ga. For. Comm. Res. Pap. 30.

Van Lear, D.H., and Waldrop, T.A. 1989. History, uses, and effects of fire in the Appalachians. USDA For. Serv. Gen. Tech. Rep. SE-54.

Waldrop, T.A. 1997. Four site-preparation techniques for regenerating pine–hardwood mixtures in the Piedmont. South. J. Appl. For. **21**: 116–122.

Walters, R.S., and Yawney, H.W. 1990. Red maple. *In* Silvics of North America Vol. 2. Hardwoods. *Compiled by* R.M. Burns and B.H. Honkala. U.S. Dep. Agric. Agric Handb. 654. pp. 60–69.

Ward, J.S., and Stephens, G.R. 1989. Long-term effects of a 1932 surface fire on stand structure in a Connecticut mixed-hardwood forest. *In* Proceedings of the 7th Central Hardwood Forest Conference, 5–8 Mar. 1989, Carbondale, Ill. *Edited by* G. Rink and C. Budelsky. USDA For. Serv. Gen. Tech. Rep. NC-132. pp. 267–273.

Wendel, G.W., and Smith, H.C. 1986. Effects of prescribed fire in a central Appalachian oak–hickory stand. USDA For. Serv. Res. Pap. NE-594.