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Using shelterwood harvests and prescribed fire to regenerate oak stands on productive upland sites

Patrick Brose[1,*], David Van Lear[2], Roderick Cooper[2]

[1] USDA Forest Service, 233 Lehotsky Hall, Clemson University, Clemson SC 29634-1003, USA
[2] Department of Forest Resources, 261 Lehotsky Hall, Clemson University, Clemson SC 29634-1003, USA

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Abstract

Regenerating oak stands on productive upland sites in the Piedmont region is a major problem because of intense competition from yellow-poplar. As a potential solution to this problem, we tested the hypothesis that a shelterwood harvest of an oak-dominated stand, followed several years later by a prescribed fire, would adequately regenerate the stand. Three oak-dominated stands, in which shelterwood harvests had been conducted several years earlier, were each divided into spring burn, summer burn, winter burn, and control treatments. Three years after the prescribed fires, oak had higher density and stocking in burned as compared to unburned areas while yellow-poplar had its highest density and stocking in the controls. Season-of-burn interacted with fire intensity to create several probable outcomes of stand development. Areas treated with high-intensity fire during the spring will develop into oak-dominated stands after just one burn. Controls and areas treated with low-intensity fire will become dominated by yellow-poplar. Other combinations of fire intensity and season-of-burn will produce mixed hardwood stands with varying proportions of oak. Combining shelterwood harvesting with prescribed fire appears to be a viable method for regenerating oak stands on productive upland sites in the Piedmont region and may be applicable elsewhere.

Keywords: *Liriodendron*; Oak regeneration; Prescribed fire; *Quercus*; Shelterwood system; Yellow-poplar

1. Introduction

Throughout the hardwood forests of eastern North America, regenerating oak (*Quercus* spp. L.) stands on productive upland sites (oak SI_{50}>18 m) presents a daunting problem to resource managers (Lorimer, 1993). Logging of such stands rarely results in regenerating the site to oak as composition drastically changes to less-desirable species (Loftis, 1983; Schuler and Miller, 1995; Cook et al., 1998). This chronic, widespread problem has led to much speculation on how prescribed fire can be used to regenerate oak-dominated stands because many of these stands originated when wildfire was more prevalent than it is now (Pyne, 1982; Van Lear and Waldrop, 1989; Abrams, 1992).

Generally, initial fire-oak research (Johnson, 1974; Teuke and Van Lear, 1982; Wendel and Smith, 1986) showed prescribed burning to be detrimental to oak regeneration but these studies examined fire as a

*Corresponding author.

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single. preharvest disturbance. Merritt and Pope (1991) and Barnes and Van Lear (1998) also studied preharvest prescribed burning but examined it from a multiple-fire perspective. These studies indicated that preharvest burning to regenerate oak would be a time-consuming process requiring multiple fires over a decade or more, which is a widely-held belief among forestry professionals (Lorimer et al., 1994).

Hannah (1987) suggested that prescribed fire be used as a follow-up treatment to an initial shelterwood harvest. Such a disturbance regime would mimic conditions prevalent when many of today's high-quality oak stands originated, namely fire after a canopy disturbance such as harvesting, ice damage, insect outbreak, or windthrow, (Pyne, 1982; Van Lear and Waldrop, 1989; Abrams, 1992).

Recent research suggests that shelterwood harvesting, followed several years later by fire, does favor oak regeneration over its competitors. In 1993, the Virginia Department of Game and Inland Fisheries (VDGIF) burned two stands previously treated with a shelterwood harvest (Keyser et al., 1996). Both contained abundant yellow-poplar (*Liriodendron tulipifera* L.) regeneration and lesser amounts of oak reproduction. They found that summer burning reduced yellow-poplar density by 96%, while oak density decreased by only 11%.

Brose and Van Lear (1998) expanded VDGIF's pilot study, examining the responses of hardwood regeneration to prescribed fires conducted during different seasons and at different intensities. VDGIF's report that oak regeneration was more resistant to fire than yellow-poplar reproduction was confirmed. Additionally, we found fire intensity to be critical in controlling yellow-poplar regeneration and that fire improved the form and growth rate of sprouting oaks. However, yellow-poplar and other competing species were still present, implying that additional burning may be necessary to ensure eventual oak domination.

In 1997, we reexamined the stands treated in 1995 with seasonal prescribed fires of varying intensities. Our objective was to examine the densities of hardwood regeneration from a spatial perspective and determine if one prescribed burn several years after the initial harvest of a two-cut shelterwood would provide adequate free-to-grow oak regeneration on productive upland sites. We attempted to define those conditions of fire intensity and timing in shelterwood situations where sufficient free-to-grow oak regeneration should result in an oak-dominated stand. This knowledge will help to formulate a fire/silvicultural prescription for regenerating oak stands on productive upland sites in the Piedmont region and it also may be applicable elsewhere.

2. Methods

2.1. Study area

This study was conducted at the Horsepen Wildlife Management Area in the Piedmont Physiographic Province of central Virginia (latitude 37°30′N, longitude 78°33′W). Topography consists of broad gently-rolling hills between 150 and 180 m elevation. Mean annual precipitation 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). Ownership and management is by the Virginia Department of Game and Inland Fisheries.

Three hardwood stands (Dunnavant, Lake Road, and Ward Farm), treated 2–4 years earlier with the initial cut of a two-cut shelterwood, were selected in 1994 for the study. According to VDGIF records, stands had similar site and stand characteristics before initial harvest (Table 1). 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).

Overstory trees in the preharvest stand numbered ca. 200/ha, of which ≈75% were upland oaks [white oak (*Quercus alba* L.), northern red oak (*Q. rubra* L.), black oak (*Q. velutina* Lam.), scarlet oak (*Q. coccinea* Muenchh.), and chestnut oak (*Q. prinus* L.)]. The remaining 25% were yellow-poplar, pignut hickory (*Carya glabra* (Miller) Sweet), and mockernut hickory (*C. tomentosa* (Poiret) Nuttall). Common midstory hardwoods included red maple (*Acer rubrum* L.), flowering dogwood (*Cornus florida* L.), blackgum (*Nyssa sylvatica* Marshall), American beech (*Fagus grandifolia* Ehrhart), American hornbeam (*Carpinus caroliniana* Walter), and sourwood (*Oxydendrum arboreum* L). The regeneration pool contained ca. 2500 stems/ha with most species represented although

Table 1
Site and stand characteristics of three hardwood stands in the Virginia Piedmont before the initial shelterwood harvest

Characteristic	Dunnavant	Lake Road	Ward Farm
Size (ha)	17	20	14
Forest type [a]	WO/NRO/BO	WO/NRO/BO	WO/NRO/BO
Basal area (m^2/ha)	28	27.5	27.5
Site index [b]	23	24	23
Soil texture	Sandy loam	Sandy loam	Sandy loam
Age [c]	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

[a] WO, white oak; NRO, northern red oak; BO, black oak (Eyre, 1980).
[b] Meters at 50 years for white oak.
[c] Determined by coring five dominant oaks at dbh in each stand.

beech, dogwood, hornbeam, and red maple predominated.

Harvesting removed most of the co-dominant oaks and low-value species, leaving 50% of the canopy (Table 2). Approximately 50–75 dominant oaks and hickories per hectare were retained for mast production. 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.

Table 2
Basal areas (m^2/ha) of major tree species in oak-dominated stands in the Virginia Piedmont 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
	Others [a]	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
	Others	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
	Others	7.1	6.1	1.0
	Yellow-poplar	1.3	0.5	0.8
	Total	27.5	16.5	13.7

[a] Includes American beech, red maple, and sweetgum.

In fall 1994, a randomized complete block study was installed to analyze season-of-burn effects on density, height growth, stem form, and total height of hardwood advance regeneration (Brose and Van Lear, 1998). Each stand was divided into four 2–5-ha treatment areas (control and spring, summer, and winter burns).

2.2. Prescribed fires

Prescribed fires were conducted in 1995 on February 25 and 27 (winter burn), April 26 (spring burn), and August 24 (summer burn) by VDGIF personnel in accordance with department policy and state law. Spring fires occurred when leaves were 50–75% expanded. Fuel and weather conditions were monitored with a belt weather kit and varied among and within seasons (Table 3). All prescribed fires were ignited 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.

Behavior of prescribed fires was measured in each treatment area. Flame length was estimated by using height reference markers placed at 0.3-m intervals to a height of 2 m on five residual trees (Rothermel and Deeming, 1980). Rate-of-spread was calculated by marking, timing, and measuring five 2-min runs per

Table 3
Environmental conditions of seasonal prescribed fires in oak-dominated shelterwood stands in the Virginia Piedmont

Conditions	Dunnavant	Lake Road	Ward Farm
Winter burn			
Burn date	2/25/95	2/27/95	2/27/95
Time-of-burn	1300	1100	1430
Air temperature (C)	8	6	9
Relative humidity (%)	26	62	54
Wind direction	NW	E	E
Wind speed [a] (km/h)	6	3	4
Cloud cover (%)	0	100	100
Fuel moisture [b] (%)	10	15	15
Spring burn			
Burn date	4/26/95	4/26/95	4/26/95
Time-of-burn	2000	1630	1830
Air temperature (C)	20	23	21
Relative humidity (%)	28	20	20
Wind direction	SW	SW	SW
Wind speed [a] (km/h)	2	8	5
Cloud cover (%)	0	0	0
Fuel moisture [b] (%)	10	10	10
Summer burn			
Burn date	8/24/95	8/24/95	8/24/95
Time-of-burn	1630	1430	1230
Air temperature (C)	33	35	35
Relative humidity (%)	56	44	46
Wind direction	SW	SW	SW
Wind speed [a] (km/h)	1	8	6
Cloud cover (%)	0	0	0
Fuel moisture [b] (%)	14	14	14

[a] Eye-level in stand at beginning of the burn.
[b] Moisture of downed woody debris between 0.64 and 2.54 cm diameter.

plot with a stopwatch. Spring fires had the most intense fire behavior with flame lengths and rates-of-spread averaging 0.8 m and 1.3 m/min, respectively. Winter and summer fires behaved similarly to spring fires on occasion; however, higher relative humidity and slower wind speed generally resulted in about a 50% reduction in flame length and rate-of-spread. Overall, prescribed burns were easily executed.

2.3. Study design and measurements

The existing randomized complete block design was re-used to study the density, stocking, and spatial patterns of oak and yellow-poplar regeneration, following seasonal prescribed fires. Thirty plots (2.6 m diameter each) were systematically located on a grid to provide uniform sampling of each treatment with a plot density of 6–15 plots/ha. Density (stems/ha) was determined by counts of oaks and yellow-poplars in each plot. Multiple sprouts from one rootstock were counted as one stem.

As we wanted to assess probable regeneration outcome, tallied stems had to meet a minimum criterion to be acceptable for counting. An acceptable oak had to have a straight stem that was >1.37 m tall in control and winter burn treatments, >1.0 m tall in the spring burn treatment, and >0.7 m tall in the summer burn treatment. Sander et al. (1976) showed that oak regeneration must be >1.37 m tall to be competitive after release. We used shorter minimum heights in the spring and summer burn areas because sprouting oaks in these treatments had less growing time after the fires (2–2.5 growing seasons) than those stems in the winter burn treatment (3 growing seasons). Also, oaks in the spring and summer burn areas sprouted with diminished root-carbohydrate reserves while their counterparts in the winter burn treatment had full root reserves (Hodgkins, 1958).

Acceptable yellow-poplars were defined as being at least one-half the minimum oak height for the treatment (0.7, 0.5, and 0.35 m tall in winter, spring, and summer treatment, respectively). We made this allowance because yellow-poplar will outgrow oak on these sites (Olson and Della-Bianca, 1959; Beck, 1981; O'Hara, 1986).

Stocking, namely the proportion of plots containing at least one acceptable oak or yellow-poplar expressed as a percentage, was used as a measure of distribution of oak and yellow-poplar regeneration in each treatment. Spatial patterning of regeneration (intra-species) near and within plots was determined using *T*-square sampling (Ludwig and Reynolds, 1988). For oak and yellow-poplar, the distance (±0.1 m) from plot center to the nearest stem and from that stem to the next nearest stem were recorded. These measurements produced an index of spatial pattern in the *T*-square equation, namely clustered, random, or uniformly distributed (Ludwig and Reynolds, 1988).

We examined inter-species spatial relationships by using a modified competition index (Heygi, 1974) for the oaks. In each plot containing acceptable oaks, the tallest, straightest oak was visually selected, designated a target oak, and its height was measured to the nearest 0.1 m. All competitors within 3.0 m of this oak were measured for height and their distance from the oak. These numbers were then used in Heygi's equation to quantify the competitive condition for each target oak.

Some target oaks had no competition within the plot nor in the surrounding area. Such oaks were designated free-to-grow (Nix, 1989). Criteria for this designation were:

1. no yellow-poplars within the plot;
2. no major competitors of equal or greater height within 3 m; and
3. no yellow-poplar stump sprouts within 4.5 m.

Major competitors were species capable of at least co-dominant status upon maturity and included yellow-poplar, pignut hickory, mockernut hickory, red maple, sweetgum (*Liquidambar styraciflua* L.), and loblolly pine (*Pinus taeda* L.). Species that would probably only attain the midstory upon maturity, namely blackgum, flowering dogwood, and hornbeam, were not considered major competitors because oak will grow past them in a few years (Nix, 1989; Waldrop, 1997). The distance of 3 m was chosen because it corresponded to Heygi's competition index and provided at least 50% of the growing space needed at maturity for the target oak.

In view of the fire intensity varying among, and within, treatments (Brose and Van Lear, 1998), plots in burned areas were assigned to one of the four levels of fire intensity based on fuel consumption during the prescribed burns. Fire behavior, fire intensity, and changes in fuel loadings throughout each treatment area had previously been documented (Brose, 1997). Low-intensity fires (flame lengths $\leq$0.3 m) partially consumed litter and small woody debris (<0.6 cm diameter), and top-killed <75% of the advance regeneration. Low-medium-intensity fire (flame lengths between 0.3 and 0.75 m) completely consumed litter and small fuels and top-killed 75–100% of the regeneration. Medium-high-intensity fire (flame lengths between 0.75 and 1.2 m) top-killed all regeneration. They also visibly reduced loadings of 2.5–7.5 cm diameter fuels, caused ca. 50% mortality of midstory trees, and scorched bark on an occasional overstory tree. High-intensity fire (flame lengths >1.2 m) visibly reduced woody debris >7.5 cm diameter, killed most midstory trees, charred bark on most overstory trees, and caused occasional mortality of an overstory tree. Assignment of plots to different fire-intensity levels (12–36 plots per level) created a 3×4 factorial design with three fire seasons and four fire-intensity levels. Using this design, we examined the effect of increasing fire intensity within season-of-burn on density, stocking, and competitive condition of oak–yellow-poplar regeneration.

2.4. Statistical analysis

Analysis of variance with Student–Newman–Kuel mean separation test was used to compare season-of-burn treatments for differences in density and clustering of oak and yellow-poplar regeneration (SAS Institute, 1993). Competitive condition of oak was tested with analysis of covariance and least-squares mean separation with regeneration age as the covariate (SAS Institute, 1993). Analysis of variance with least-squares mean separation was used to test for differences among these variables as fire intensity interacted with season-of-burn (SAS Institute, 1993). Chi-square analysis was used to compare differences in stocking among treatments and among fire intensities within season-of-burn (SAS Institute, 1993). In all tests, α=0.05 and data were rank-transformed as needed to correct unequal variances and non-normality of residual values.

3. Results

Although designed as a randomized complete block study, trends in density, stocking, and spatial patterns of oak and yellow-poplar regeneration were consistent among stands. Therefore, data were pooled to simplify reporting.

3.1. Preburn conditions

Previous research in the same stands (Brose and Van Lear, 1998) showed that before burning yellow-poplar was more abundant, faster growing, and taller than oak in all treatments (Table 4). Its stocking ranged from 82 to 91%, indicating widespread distribution. Oak reproduction was also widely distributed (stocking ranged

Table 4
Preburn characteristics (mean±1 se) of oak and yellow-poplar advance regeneration in shelterwood stands in the Virginia Piedmont

Species	Density [a] (stems/ha)	Total height [a] (m)	Height growth [a] (m/year)	Stocking [a] (%)
Control				
Oak	1578±163b	0.83±0.03b	0.17±0.01b	83±7a
Yellow-poplar	5572±996a	1.20±0.10a	0.38±0.03a	85±4a
Spring burn				
Oak	2376±263b	1.17±0.09b	0.26±0.03b	87±6a
Yellow-poplar	5901±800a	1.55±0.14a	0.43±0.02a	91±6a
Summer burn				
Oak	3038±543b	0.86±0.05b	0.19±0.02b	88±5a
Yellow-poplar	9957±962a	1.60±0.08a	0.35±0.02a	90±7a
Winter burn				
Oak	1771±185c	1.18±0.09b	0.27±0.02b	86±5a
Yellow-poplar	7311±973a	2.04±0.19a	0.49±0.04a	82±81

[a] Means followed by different letters are different within that treatment and column (α=0.05).

from 83 to 88%) but was outnumbered 3 : 1 by yellow-poplar. Oak was shorter and growing slower than yellow-poplar. Free-to-grow oaks were sparse to absent due to the abundance of taller yellow-poplar regeneration.

3.2. Postburn conditions

3.2.1. Density

Oaks were about three times more abundant in burned areas than in unburned controls, while yellow-poplar density in burned areas was less than half its density in unburned controls (Fig. 1). Yellow-poplar outnumbered oak by about 8 : 1 in the control while both species had equivalent densities in all fire treatments.

Within the three fire treatments, oak regeneration was most abundant in the high-intensity spring burn and the low-to-medium intensity summer burn (Table 5). Elsewhere, its density was about equal regardless of season-of-burn and fire intensity. Yellow-poplar density was highest in low-intensity areas,

Table 5
Density (mean stems/ha±1 se) of oak and yellow-poplar regeneration after four different levels of fire intensity in the Virginia Piedmont

Species	Fire Intensity Levels Low	Low medium	Medium high	High
Spring burn				
Oak	1694±600C [a]b [b]	1709±571B [a]b [b]	2385±571AB [a]b [b]	4160±511A [a]a [b]
Yellow-poplar	5567±1887AB [a]a [b]	2776±682B [a]a [b]	3685±1047A [a]a [b]	1134±699C [a]b [b]
Summer burn				
Oak	2724±813BC [a]b [b]	4945±1077A [a]a [b]	2043±701AB [a]b [b]	2389±499B [a]b [b]
Yellow-poplar	4051±1037B [a]a [b]	3631±1158AB [a]	1134±921B [a]ab [b]	573±131C [a]b [b]
Winter burn				
Oak	2006±737C [a]b [b]	1955±436B [a]b [b]	1961±538AB [a]b [b]	3111±402B [a]a [b]
Yellow-poplar	9077±2418A [a]a [b]	2823±714AB [a]b [b]	1470±647B [a]bc [b]	865±694C [a]c [b]

[a] Means with different uppercase letters are different within that column (α=0.05).
[b] Means with different lowercase letters are different within that row (α=0.05).

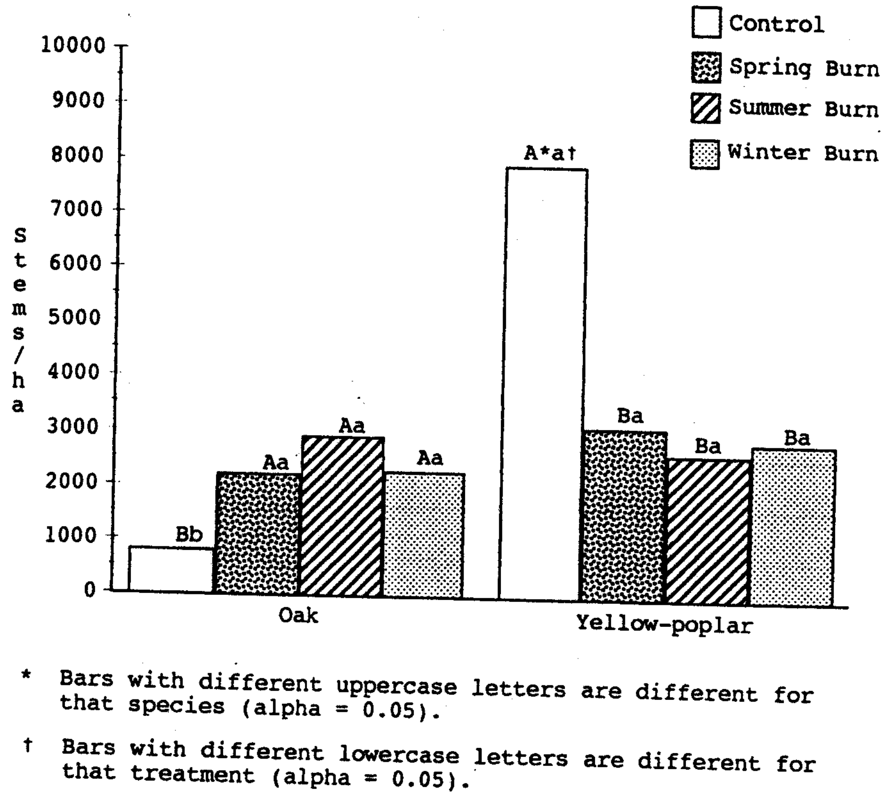


Fig. 1. Density of oak and yellow-poplar advance regeneration after seasonal prescribed fires in shelterwood stands in the Virginia Piedmont.

where it outnumbered oak. At the two medium intensities, densities of the two species were equivalent but oak exceeded yellow-poplar density at high fire intensities.

3.2.2. Stocking

Oak stocking was highest in the spring burn (66%), followed by summer (60%), winter (53%), and control (37%) (Fig. 2). Conversely, yellow-poplar stocking was greatest in the control (77%) and less in all three fire treatments. Oak exceeded yellow-poplar stocking in the three fire treatments while the relationship was reversed in the control.

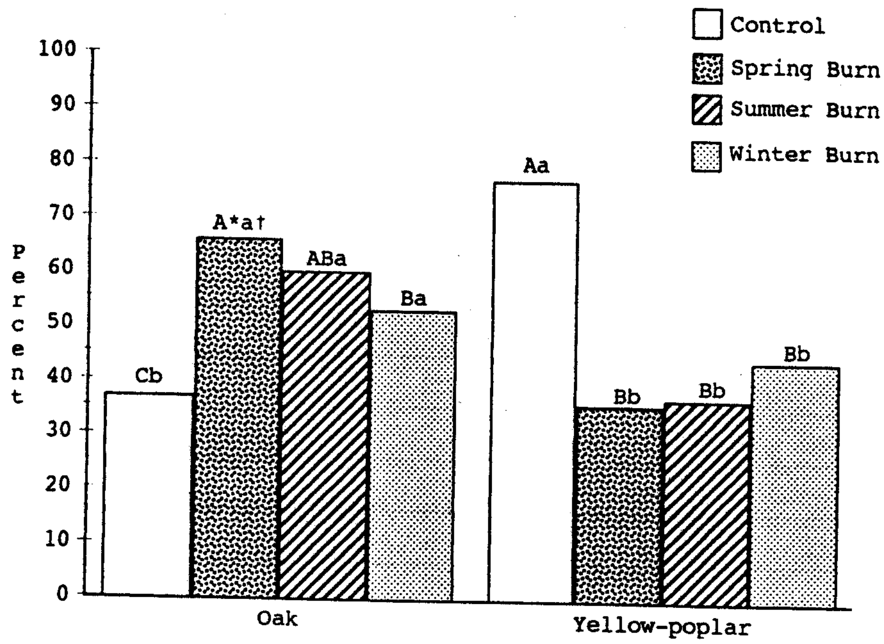
Within the three fire treatments, oak stocking patterns among fire intensities were similar to those for density (Table 6). Stocking was least in the high-intensity summer burn (42%) and greatest in the low-medium summer burn (79%). Otherwise oak stocking varied little among season-of-burn and fire intensity, ranging from 47 to 67%. Yellow-poplar stocking was highest in the low-intensity burn areas (72–92%). Stocking rates decreased as fire intensity increased, especially in the spring and summer burn treatments. Generally, yellow-poplar equalled or exceeded oak stocking at low fire intensities while the opposite was true at high fire intensities.

3.2.3. Intra-species spatial pattern

Oak and yellow-poplar regeneration differed in spatial arrangement in each treatment (Fig. 3). Yellow-poplar scored between 0.64 and 0.73 on a 0–1 scale, indicating that it occurred in clusters (Ludwig and Reynolds, 1988). Oak scored between 0.27 and 0.39, indicating it occurred as uniformly distributed individuals. Neither treatments nor fire intensities affected distribution patterns for either species.

3.2.4. Intra-species competitive relationship

Oaks occupied a stronger competitive position in all fire treatments (Heygi index≈0.24), than in the



* Bars with different uppercase letters are different for that species (alpha = 0.05).

† Bars with different lowercase letters are different for that treatment (alpha = 0.05).

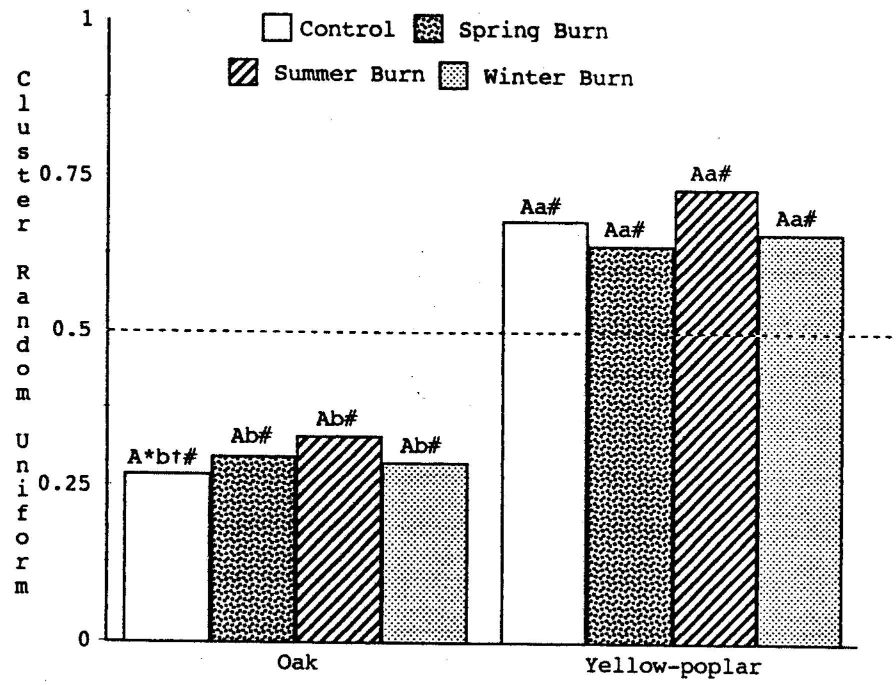
Fig. 2. Stocking of oak and yellow-poplar advance regeneration after seasonal prescribed fires in shelterwood stands in the Virginia Piedmont.

control (index≈0.35) (Table 7). Competitors were more numerous and closer to the oaks in the control than in the fire treatments. Among treatments, oaks and competitors were tallest in the control, next tallest in the winter burn, intermediate in the spring burn, and shortest in the summer burn. In all

Table 6
Stocking percent (mean±1 se) of oak and yellow-poplar regeneration after four different levels of fire intensity in the Virginia Piedmont

Species	Fire Intensity Level Low	Low medium	Medium high	High
Spring burn				
Oak	64±25AB [a]ab [b]	63±13AB [a]ab [b]	53±9Bb	48±15Aa
Yellow-poplar	83±27AB [a]a [b]	58±16AB [a]ab [b]	44±10B [a]ab [b]	21±15CD [a]b [b]
Summer burn				
Oak	54±8B [a]b [b]	79±11A [a]a [b]	56±18B [a]b [b]	42±20BC [a]b [b]
Yellow-poplar	72±12B [a]a [b]	45±12B [a]a [b]	13±D [a]b [b]	10±10D [a]b [b]
Winter burn				
Oak	50±8B [a]b [b]	47±11B [a]b [b]	67±5A [a]a [b]	52±14B [a]b [b]
Yellow-poplar	92±8A [a]a [b]	56±6B [a]b [b]	49±5C [a]c [b]	14±14D [a]c [b]

[a] Means with different uppercase letters are different within that column (α=0.05).
[b] Means with different lowercase letters are different within that row (α=0.05).



* Bars with different uppercase letters are different for that species (alpha = 0.05).
† Bars with different lowercase letters are different for that treatment (alpha = 0.05).
\# Signifies that bar is different from mean random value of 0.5 (alpha = 0.05).

Fig. 3. Spatial pattern of oak and yellow-poplar regeneration after seasonal prescribed fires in shelterwood stands in the Virginia Piedmont.

treatments, competitors were taller than oaks. No differences in average distance to the nearest competitor were detected among the three fire treatments.

Distance to the nearest non-oak competitor increased in all fire treatments as fire intensity increased (Table 8). Conversely, density of these competitors decreased in all burned areas as fire intensity increased. Heights of oaks and competitors were not affected by increasing fire intensity, nor was Heygi's competitive index although it tended to increase as fire intensity increased.

Table 7
Competitive status (mean±1 se) of oaks 3-years after seasonal prescribed fires in shelterwood stands in the Virginia Piedmont

Treatment	Oak height (m)	Number of competitors (stems/plot)	Competitor height (m)	Distance to nearest competitor (m)	Heygi competition index
Control	2.4±1A [a]b [b]	7.6±0.8A [a]	2.9±0.1A [a]a [b]	0.8±0.1B [a]	0.35A [a]
Spring burn	1.6±1C [a]b [b]	5.3±0.3C [a]	2.0±0.1C [a]a [b]	1.3±0.1A [a]	0.25B [a]
Summer burn	1.1±1D [a]b [b]	4.7±0.3C [a]	1.5±1D [a]a [b]	1.3±0.1A [a]	0.23B [a]
Winter burn	1.9±1B [a]b [b]	6.0±0.1B [a]	2.5±0.1B [a]a [b]	1.2±0.1A [a]	0.25 [a]

[a] Means followed by different uppercase letters are different within that column (α=0.05).
[b] Height means followed by different lowercase letters are different from each other within the row (α=0.05).

Table 8
Competitive status (mean±1 se) of oaks three years after seasonal prescribed fires in shelterwood stands in the Virginia Piedmont

Fire intensity	Oak height (m)	Number of competitors (stems/plot)	Competitor height (m)	Distance to nearest competitor (m)	Heygi competition index
Spring burn					
Low	1.6±0.2AB [a]b [b]	7.7±1.4A [a]	2.2±0.3A [a]a [b]	1.1±0.2A [a]	0.29A [a]
Low-to-medium	1.6±0.2AB [a]b [b]	6.6±1.0AB [a]	2.1±3A [a]a [b]	1.2±0.2A [a]	0.26A [a]
Medium-to-high	1.4±0.2AB [a]b [b]	4.7±0.5BC [a]	2.0±0.2A [a]a [b]	1.3±0.1A [a]	0.22A [a]
High	1.5±0.2AB [a]b [b]	3.8±0.5C [a]	1.9±0.1A [a]a [b]	1.3±0.1A [a]	0.22A [a]
Summer burn					
Low	1.1±0.1B [a]b [b]	8.8±1.5A [a]	1.4±0.2B [a]a [b]	0.8±0.1B [a]	0.27A [a]
Low-to-medium	1.1±0.2B [a]b [b]	3.8±0.9B [a]	1.5±0.2B [a]a [b]	1.3±0.1A [a]	0.22A [a]
Medium-to-high	1.1±0.1B [a]b [b]	4.8±0.8B [a]	1.5±0.1B [a]a [b]	1.3±0.2A [a]	0.23A [a]
High	1.1±0.2B [a]b [b]	2.2±0.4B [a]	1.4±0.1B [a]a [b]	1.5±0.2A [a]	0.19A [a]
Winter burn					
Low	2.1±0.3A [a]b [b]	5.9±1.1AB [a]	2.7±0.3A [a]a [b]	0.9±0.2A [a]	0.27A [a]
Low-to-medium	1.7±0.2A [a]b [b]	6.8±0.7A [a]	2.4±0.2A [a]a [b]	1.1±0.1A [a]	0.24A [a]
Medium-to-high	2.0±0.3A [a]b [b]	6.0±10.2AB [a]	2.3±0.4A [a]a [b]	1.1±0.2A [a]	0.23A [a]
High	1.9±0.2A [a]b [b]	4.5±0.8B [a]	2.7±0.3A [a]a [b]	1.4±0.2A [a]	0.25A [a]

[a] Means followed by different uppercase letters are different within that column (α=0.05).
[b] Height means followed by different lowercase letters are different from each other within that row (α=0.05).

There were more free-to-grow oaks in the spring and summer burns (425 and 363 stems/ha, respectively) than in the controls and winter burns (82 and 141 stems/ha, respectively) (Fig. 4). Within the spring burn, free-to-grow oaks were most numerous (832 stems/ha) in high-intensity areas, nearly absent (5 stems/ha) in low-intensity areas, and intermediate in abundance (321 and 373 stems/ha) in the two medium-intensity areas. Summer fire resulted in substantial numbers of free-to-grow oaks in all fire intensity levels with most occurring in the two medium levels. In contrast, the winter burn had almost no free-to-grow oaks at low fire intensity, 101 and 173 stems/ha at the two medium intensities, and 259 stems/ha at high fire intensity.

Stocking of free-to-grow oaks was greater in the spring and summer burns (23 and 20%, respectively) than in the controls and winter burns (4 and 8%, respectively) (Fig. 5). Within the spring burn treatment, stocking increased from 1% at low intensity to 46% at high intensity. The summer burns had equivalent stocking of free-to-grow oak in the two medium and the high fire intensities (22–31%). In the winter burn, stocking gradually increased from 1 to 14% as fire intensity increased.

4. Discussion

4.1. Effects of burning on advance regeneration

Oak regeneration benefited from all fire treatments as its density and stocking were greater in burned areas than in the control. Conversely, prescribed burning had a negative impact on yellow-poplar advance regeneration. Before and/or without fire, yellow-poplar was extremely abundant and widespread, occurring in clusters throughout the stands. Burning reduced its density and stocking, resulting in fewer and smaller clusters of the species. These responses are due to fire intensity and season-of-burn interacting with each other and to different developmental characteristics of oak and yellow-poplar.

Fire intensity and season-of-burn appear to play important roles in shaping the composition of the regeneration pool. Fire intensity can be thought of as 'how much' fire was applied, that is a dosage rate, and season-of-burn or timing as 'when'. Both must be considered concurrently because they interact. That interaction was evident in areas receiving medium-to-high intensity fires during the growing season by the sparsity of yellow-poplar regeneration and low stock-

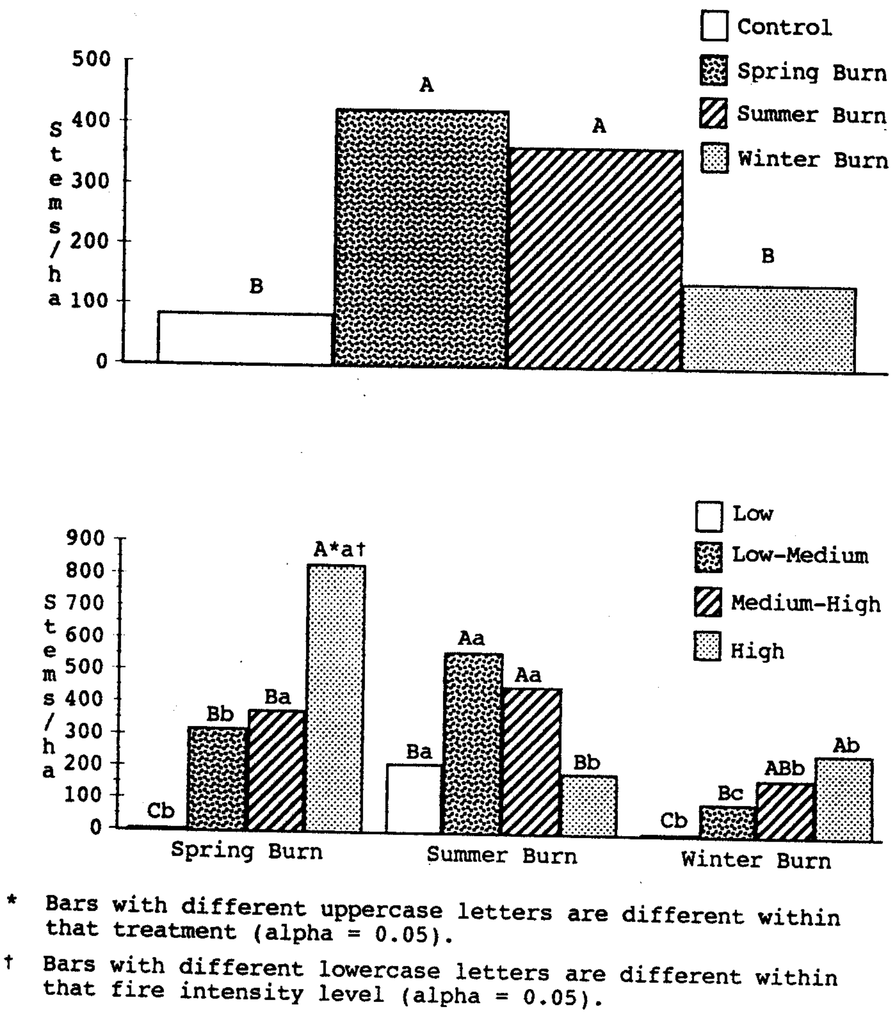
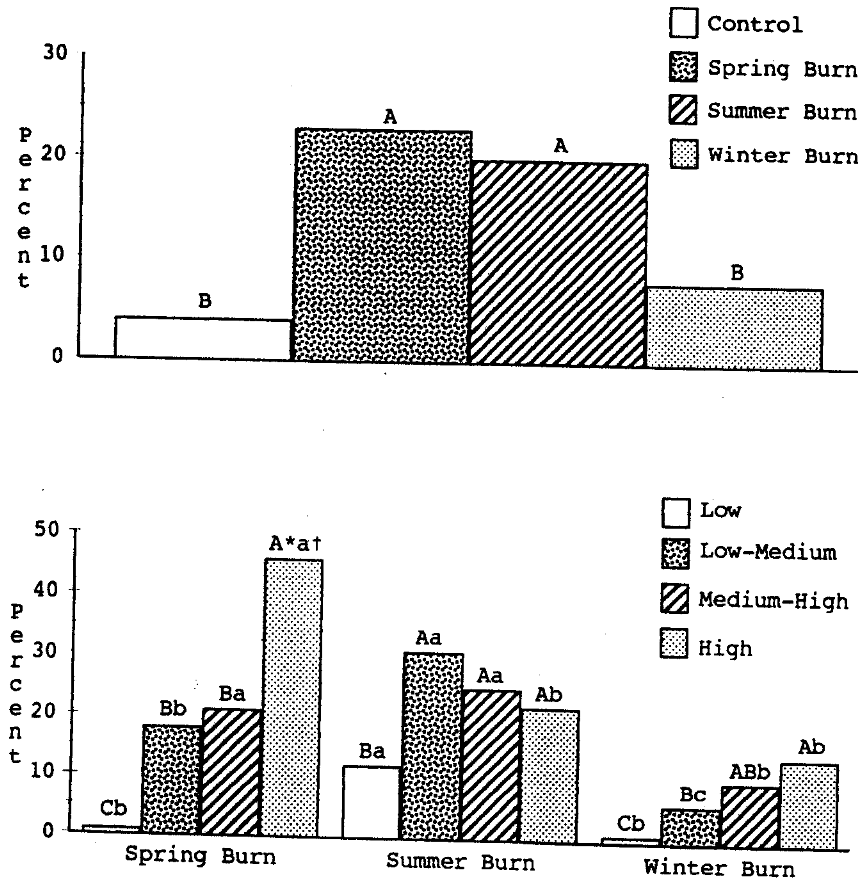


Fig. 4. Density of free-to-grow oaks among treatments and among fire intensity levels within season-of-burn in shelterwood stands in the Virginia Piedmont.

ing rates coupled with abundant free-to-grow oaks with reasonable stocking. Conversely, yellow-poplar regeneration was abundant and well stocked while free-to-grow oaks were rare and poorly stocked where low-intensity fire occurred during the winter.

The season-of-burn and accompanying fire intensity are important because they manifest differences between oaks and yellow-poplars. Acorns are frequently buried by wildlife (Darley and Johnson, 1981; Galford et al., 1988) whereas seeds from yellow-poplar are probably not, at least to the same degree. Differences between species in seed burial by wildlife are accentuated by dissimilar germination strategies.

Oak has hypogeal germination (cotyledons remain in seed), causing the root collar and its complement of dormant buds to be below the soil surface (Burns and Honkala, 1990). Yellow-poplar, in contrast, has epigeal germination (cotyledons emerge from seed), placing the root collar and its accompanying dormant buds at or above the soil surface (Beck, 1981). The number of dormant buds is probably finite; hence, if they are all killed the seedling cannot sprout regardless of the condition of the root system. Therefore, an oak



* Bars with different uppercase letters are different within that treatment (alpha = 0.05).

† Bars with different lowercase letters are different within that fire intensity level (alpha = 0.05).

Fig. 5. Stocking of free-to-grow oaks among treatments and among fire-intensity levels within season-of-burn in shelterwood stands in the Virginia Piedmont.

seedling whose dormant buds are below ground level and, therefore, somewhat insulated will more likely survive a surface fire than a yellow-poplar seedling whose dormant buds are exposed to lethal temperatures at or above the ground level.

Oak reproduction emphasizes root development rather than shoot growth in their early years, while yellow-poplar does the opposite (Kelty, 1988; Kolb et al., 1990). As a result, oak regeneration has a larger taproot mass than comparably sized yellow-poplar (Barnes and Van Lear, 1998). Large taproots are a competitive advantage after growing-season fires, because they contain more stored reserves to expend on new shoot and leaf growth (Hodgkins, 1958; Langdon, 1981). They also fuel vigorous height growth for years (Lloyd and Waldrop, 1993; Waldrop, 1997).

4.2. Probable stand development pathways

Predictions of stand development following this shelterwood-burn treatment must be made in light of the competing species (Ross et al., 1986; Kays et al., 1988). In the Piedmont, major species or species groups are oak, yellow-poplar, loblolly pine, sweetgum, hickory, and red maple (Kays et al., 1988). Oak, yellow-poplar, and loblolly pine commonly dominate productive upland sites, with yellow-poplar and loblolly pine frequently dominating to the exclusion of all other species (Olson and Della-Bianca, 1959; Beck, 1981; Lloyd and Waldrop, 1993; Waldrop, 1997). Sweetgum dominates some sites early in stand development but eventually gives way to oak (Meadows and Hodges, 1997). Hickory and red maple generally occur only as associates to oak and the latter is prone to several rots that limit its long-term competitive ability (Burns and Honkala, 1990). Thus, in the Piedmont, the proportion of oak, yellow-poplar, and loblolly pine in the regeneration pool defines how a stand will develop.

There are no oak regeneration guidelines designed specifically for the Piedmont, although they exist for other regions. Sander et al. (1976) demonstrated that, for oak regeneration to be successful in the Midwest, a minimum density of 1070 stems/ha that were at least 1.37 m tall at 59% stocking was needed before harvest. If this requirement is met, the new stand should develop with a substantial oak component. However, yellow-poplar is not a major competitor in the Midwest (Beck, 1981), with the result that in the Piedmont this guideline may indicate adequate oak regeneration when in fact it does not exist.

Clatterbuck and Meadows (1993) recommended evaluating productive bottomland sites three years after harvest to determine regeneration status. If there are at least 370 free-to-grow oak stems/ha that are well distributed, the stand is considered regenerated to oak. However, competition is generally more intense (i.e. greater stem density) in bottomlands than on uplands, with the result that in the Piedmont this criterion may indicate inadequate oak regeneration when in fact it does exist.

In this study, the interaction of season-of-burn and fire intensity created multiple pathways of stand development (Fig. 6). All areas experiencing high-intensity fire especially spring, or medium-high-intensity fire during the summer will probably mature into oak-dominated stands, containing 75–80% oak. These areas have abundant, well-distributed oak regeneration with many oaks being free to grow. Yellow-poplar was present but poorly distributed, occurring primarily in a few small clusters when it was found. Clustered yellow-poplar stems will compete against each other and, eventually, only a few will reach the upper canopy. Small numbers of hickory growing about as fast as oak were present but loblolly pine and sweetgum were absent. Red maple stump sprouts were abundant but rot should curtail its long-term growth and survival.

Areas treated with medium-high intensity fire during the spring or winter or with low-medium intensity fire during the summer should develop into oak/yellow-poplar stands comprising ca. 50% of each species (Fig. 6). These areas were similar to the high-intensity areas regarding oak regeneration and status of loblolly pine, hickory, red maple, and sweetgum. However, density and stocking of yellow-poplar were much greater in these areas, averaging 2930 stems/ha and 46%, respectively, indicating that yellow-poplar would be a formidable competitor.

The low-medium intensity fire during the spring or winter burn will probably lead to a mixed hardwood stand containing a substantial component of yellow-poplar but other species will be present (Fig. 6). These areas had acceptable density and stocking of oak but hickory, loblolly pine, red maple, and sweetgum reproduction were also present. The spring burn area had 325 stems/ha of free-to-grow oak but at only 18% stocking and yellow-poplar was abundant and well stocked in both areas.

The control treatment and all areas treated with low-intensity fire, regardless of season, will probably become stands dominated by yellow-poplar (Fig. 6). Yellow-poplar regeneration was abundant, well distributed, tall, and growing vigorously. Oak density was low and there were only 81 free-to-grow oaks/ha, most of which were stump sprouts that were not well anchored and subject to rot (Roth and Hepting, 1943). Stocking was only 37%, indicating that a large portion of the control lacked oak regeneration. A few seedling sprouts met the minimum-height criteria but they were crooked and growing slowly. The control was well stocked with oak regeneration <1.37 m tall that was buried beneath yellow-poplar and other hardwood regeneration.

Depending on management objectives, any of the previous scenarios may be valuable for resource managers. Stands containing large proportions of oak are prized for timber production and wildlife habitat. Mixed hardwood stands may be equally valuable

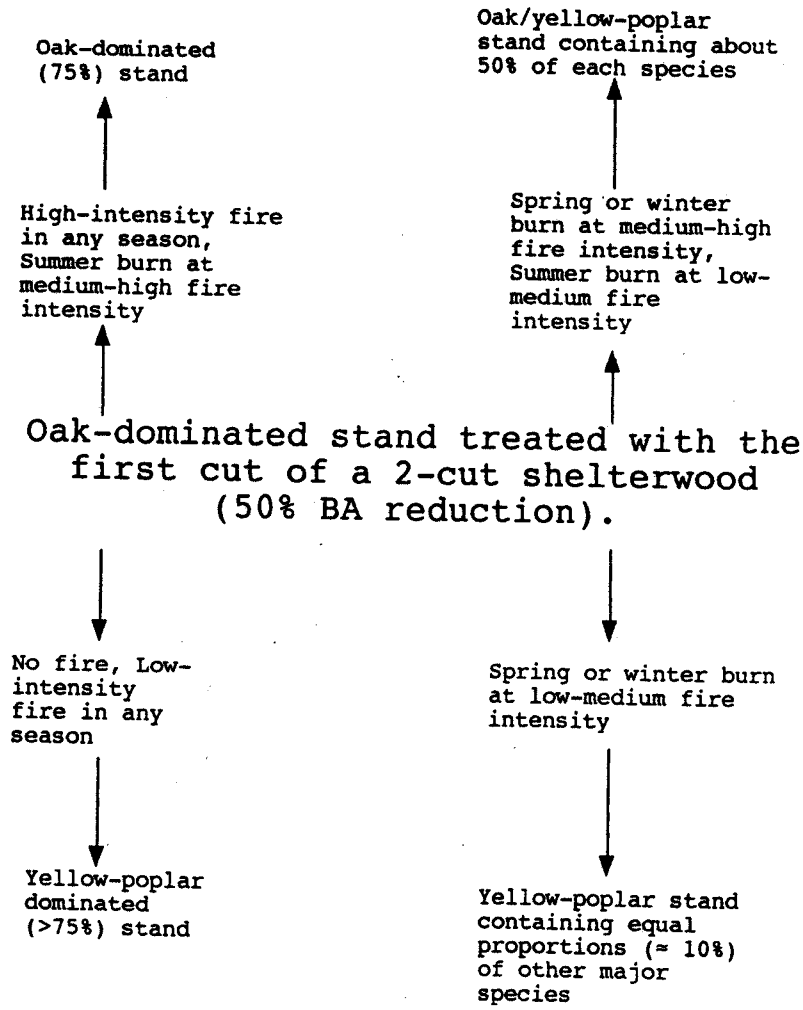


Fig. 6. Predicted development pathways of an oak-dominated stand in the Virginia Piedmont regenerated with shelterwood harvesting followed by a single seasonal prescribed fire.

because such stands are less damaged by gypsy moth (*Lymantria dispar* L). Also, development of the hardwood pulp market means fast-growing yellow-poplar can be harvested as a mid-rotation product, providing more income for the owner.

4.3. Combining fire and partial harvests

In mixed hardwood forests, the role of fire as an ecologically important disturbance is beginning to be understood and appreciated. Historically, natural disturbances such as insect outbreaks, ice storms, passenger pigeon activity, or wind events created canopy openings of varying extent in the eastern hardwood forest (Lorimer, 1980; Runkle, 1990). The resulting debris and openings predisposed the forest to fire by elevating fuel loadings, facilitating air movement, and increasing sunlight penetration (Myers and Van Lear, 1998). The increased insolation is especially important because dense shade slows the development of oak regeneration (Lorimer et al., 1994). A shelterwood harvest mimics these moderate canopy disturbances.

Native Americans frequently used fire to manipulate their environment for numerous reasons (Pyne, 1982; Denevan, 1992). Many of their burns would have been in stands previously impacted by moderate canopy disturbances. Settlers adopted these burning practices which, in conjunction with their frequent partial harvests, resulted in a harvest/fire disturbance combination (Pyne, 1982; Van Lear and Waldrop, 1989; Abrams, 1992). The combination of these paired disturbances probably played a significant role in creating and maintaining oak-dominated stands on productive upland sites.

4.4. *Timing of prescribed fires*

An interval of several years between the initial harvest cut and burning is probably critical. This allows oak reproduction to develop relatively large root systems (Kelty, 1988; 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, making it more vulnerable to surface fires. Shearin et al. (1972) showed that many yellow-poplar seeds survive fires but seedlings have little tolerance of fire (Barnes and Van Lear, 1998). The partial shade also slows yellow-poplar height growth (Beck, 1981) which prolongs their vulnerability to fires.

Spring is probably the best season for prescribed burning in oak-dominated shelterwood stands because favorable weather conditions (warm temperatures, low humidities, sunny days, and southerly winds) are common, creating numerous opportunities for medium-high and high-intensity fires. Summer and winter probably present fewer opportunities for medium-high intensity fires as both have conditions – higher humidities, partial shade, cooler ambient temperatures, and low insolation levels – that will limit fire intensity. This limitation was evident in this study; large areas burned at medium-high and high intensity during the spring but only small areas burned at the same intensities during the summer and winter.

More research concerning the shelterwood-fire influence on oak regeneration is warranted to answer questions arising from this study. Will these stands develop as we predict? Is this approach applicable in other regions where different competing species and environmental conditions may influence the outcome of this dual disturbance regime? What are the implications of this approach to understory plants and wildlife species? Prescribed fire appears to have a place in oak management. Answering the above questions, as well as others, will provide more specific guidance for resource managers seeking to maintain oaks on productive sites.

5. Conclusions

A single prescribed fire can regenerate oak stands on productive upland sites in the Piedmont region. To do so, this fire must be conducted several years after the initial harvest of a two-cut shelterwood and be of medium-high to high intensity. This type of fire is most easily conducted during the spring and should result in adequate free-to-grow oak regeneration to dominate the new stand. Medium-intensity fires will produce mixed hardwood stands with varying proportions of oak. Low-intensity fires have little or no effect on stand composition, namely shelterwood stands treated in this manner will develop into yellow-poplar dominated stands. This shelterwood-burn technique appears to be a promising solution to the long-standing problem of regenerating oaks on productive upland sites in the Piedmont and may be applicable elsewhere.

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