Forest Ecology and Management 260 (2010) 1516–1524

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

# Long-term effects of single prescribed fires on hardwood regeneration in oak shelterwood stands

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ARTICLE INFO

*Article history:*
Received 24 May 2010
Received in revised form 29 July 2010
Accepted 30 July 2010

*Keywords:*
*Quercus*
*Carya*
*Liriodendron tulipifera*
*Acer rubrum*
Prescribed fire
Shelterwood

ABSTRACT

One of the arguments against using prescribed fire to regenerate oak (*Quercus* spp.) forests is that the improvement in species composition of the hardwood regeneration pool is temporary and multiple burns are necessary to achieve and maintain oak dominance. To explore this concern, I re-inventoried a prescribed fire study conducted in the mid-1990s to determine the longevity of the effects of a single prescribed fire on hardwood regeneration. The initial study was conducted in three oak shelterwood stands in central Virginia, USA. In 1994, each stand was divided into four treatments (spring, summer, and winter burns and a control) and the hardwood regeneration was inventoried before the fires. During the burns, fire intensity was measured and categorized in each regeneration sampling plot. Second-year postfire data showed marked differences in species mortality rates, depending on season-of-burn and fire intensity: oak and hickory (*Carya* spp.) regeneration dominated areas burned by medium- to high-intensity fire during the spring and summer while yellow-poplar (*Liriodendron tulipifera*) and red maple (*Acer rubrum*) seedlings dominated unburned areas and all areas treated with low-intensity fire regardless of season-of-burn. The treatments were re-inventoried in 2006 and 2007 to determine whether these fire effects were still present. The new data show that the species distributions by season-of-burn and fire intensity found in 1996 still existed 11 years after the treatments. The fact that fire effects in oak shelterwood stands can last at least a decade has important management implications for resource professionals interested in sustaining oak forests in the eastern United States.

## 1. Introduction

In the past 10–15 years, managers and researchers have come to recognize the importance of periodic surface fires in perpetuating oak (*Quercus* spp.) forests in eastern North America (Yaussy, 2000; Dickinson, 2006; Hutchinson, 2009). However, incorporating prescribed burning into oak forest management is slow for several reasons including the perception that the effects of a single fire are ephemeral and multiple burns spread over several years are required to produce meaningful changes in species composition (Van Lear and Watt, 1993). This perception is understandable. Most of the early fire/oak research reported results from single burns, either a wildfire or a prescribed fire (Brose et al., 2006). Sometimes oak regeneration benefited from fire (Brown, 1960; Swan, 1970; Ward and Stephens, 1989), sometimes it was harmed (Johnson, 1974; Wendel and Smith, 1986; Loftis, 1990), and sometimes effects were negligible (Teuke and Van Lear, 1982; Merritt and Pope, 1991). Simard (1983) surmised that this inconsistency of results arose from several sources; (1) inadequate or no measures of fire behavior (especially intensity), fuel loading, weather conditions, or stand characteristics, (2) lack of an unburned control or replication of treatments, and (3) reporting short-term (1- or 2-year postburn) results.

From 1994 to 1997, my major professor and I conducted a prescribed fire study specifically designed to avoid the first two shortcomings listed above and learn why such disparate results were being reported in the literature (Brose and Van Lear, 1998; Brose et al., 1999). In that project, seasonal prescribed fires (spring, summer, winter, and an unburned control) were conducted in 1995 in three similar oak shelterwood stands. Within each stand, every treatment block was described in detail regarding preburn forest regeneration and fuel conditions. Fire intensity was measured and categorized. Regeneration inventories were repeated in late 1996 and 1997 (2-year postburn). Study results showed that postfire mortality of hardwood regeneration varied by species based on fire seasonality, fire intensity, and their interaction. Red maple (*Acer rubrum*) and yellow-poplar (*Liriodendron tulipifera*) regeneration had higher mortality rates than hickory (*Carya* spp.) and oak reproduction as season-of-burn changed from winter to spring to summer and fire intensity increased from low to high (Fig. 1).

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0378-1127/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.foreco.2010.07.050

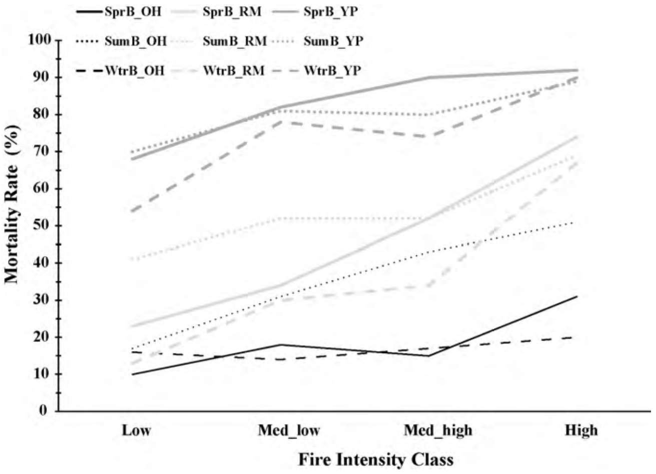

**Fig. 1.** The differential mortality rates of hardwood regeneration growing in oak shelterwood stands when subjected to seasonal prescribed fires of varying intensities (Brose and Van Lear, 1998). Abbreviations are: WtrB = winter burn, SprB = spring burn, SumB = summer burn, OH = oak/hickory combined, RM = red maple, and YP = yellow-poplar.

These differential mortality rates translated into oak and hickory dominating areas treated with medium to high-intensity fire in the spring or summer while yellow-poplar and red maple dominated unburned areas, those treated with low-intensity fire in any season, or winter fire. What was not answerable at the time was whether these 2-year results were temporary or long-lasting.

Long-term fire studies in oak forests have recently become relatively common in the literature (Dey and Hartman, 2005; Hutchinson et al., 2005; Albrecht and McCarthy, 2006; Blankenship and Arthur, 2006; Alexander et al., 2008; Iverson et al., 2008; Green et al., 2010). All of these recent studies are well designed and implemented to avoid the shortcomings of the early fire/oak studies. Also, they involve multiple fires conducted on a periodic basis over several years to a decade or more and some combine burning with overstory thinning. However, the time between the latest fire and data collection is generally short (1–3 growing seasons). Consequently, they cannot address whether the fire effects are transient or long-lasting. One study that does have a long response period is that of Ward and Stephens (1989). In that paper, they reported on stand development of a young hardwood forest that was partially burned by a wildfire in 1932. In the burned area, oak and hickory dominated the overstory while the canopy of the unburned section consisted primarily of black birch (*Betula lenta*) and red maple. Clearly, more studies documenting long-term development of young hardwood stands originating from fire alone or in combination with other silvicultural treatments are needed and would be beneficial to forest managers.

In 2006 and 2007, the opportunity arose to re-inventory the regeneration of the three oak shelterwood stands used in the Brose and Van Lear (1998) paper. The objective of this re-inventory was to determine whether the relationships among fire seasonality, fire intensity, and species dominance (abundance and height) were still evident as the regeneration grew into saplings and formed a new forest. Specific predictions made in 1996–1997 about stand development were (1) yellow-poplar would dominate in the control and all seasonal burns treated with low-intensity fire, (2) red maple and yellow-poplar would dominate spring and winter burns conducted at medium-low intensity, (3) there would be no dominant species in areas burned with medium-high spring or winter fire or medium-low summer fire, and (4) oak would dominate areas experiencing medium-high summer fires or high-intensity fire in any season (Brose et al., 1999). Knowing if the effects of single prescribed fires persist into the second decade of stand development is important to land managers trying to sustain oak forests in an economical, efficient manner.

## 2. Methods

### 2.1. Study site

This study was conducted at the Horsepen Wildlife Management Area in the Piedmont region of central Virginia (lat 37°30′N, long 78°33′W). This area consists of broad, gently rolling hills at elevations between 150 and 180 m above sea level. Soils are deep, well-drained sandy loams (Typic Hapludult) formed in place from gneiss, granite, and schist parent material (Reber, 1988). Mean monthly temperatures range from 4 °C in January to 24 °C in July. Annual precipitation is 110 cm distributed evenly throughout the year. The growing season averages 190 days. The area is owned and managed by the Virginia Department of Game and Inland Fisheries (VDGIF).

Three oak shelterwood stands (Dunnavant, Lake Road, and Ward Farm) were selected in 1994 for the study based on similarity of site characteristics, species compositions, and treatment histories. Increment coring of five dominant oaks in each stand indicated that the stands were even-aged, about 100 years old, and that oak site index (base age 50) ranged from 20 to 25 m. Common overstory trees included white oak (*Quercus alba*), northern red oak (*Quercus rubra*), scarlet oak (*Quercus coccinea*), black oak (*Quercus velutina*), pignut hickory (*Carya glabra*), mockernut hickory (*Carya tomentosa*), and yellow-poplar. Common midstory trees included red maple, flowering dogwood (*Cornus florida*), blackgum (*Nyssa sylvatica*), serviceberry (*Amalanchier arborea*), American beech (*Fagus grandifolia*), and sourwood (*Oxydendrum arboreum*). According to VDGIF records, pre-shelterwood basal areas averaged 28 $m^2$/ha. The stands had been damaged by ice storms in the late 1980s. Dunnavant and Ward Farm received the first cut of a 2-stage shelterwood harvest in summer 1990 and Lake Road was similarly cut in winter 1992. Those harvests removed the damaged trees as well as many of the midstory and low-value stems. Residual basal areas after the shelterwood harvest averaged 13 $m^2$/ha and canopy cover was about 50%.

### 2.2. Study design and implementation

A randomized complete block experiment was installed to evaluate season-of-burn effects on hardwood regeneration. Each stand was divided into four 2- to 5-ha areas and each area was randomly assigned to one of four treatments (spring, summer, or winter burn, or unburned control). Within each treatment area, fifteen 20-$m^2$ circular plots were systematically located to uniformly cover the area. Within each plot, the number of hardwood regeneration stems between 0.3 and 3.0 m tall was determined by identifying each stem to species and tallying it into one of five groups (hickory, oak, red maple, yellow-poplar, or miscellaneous). Red maple and yellow-poplar were species-specific groups while the oak group included the four oaks listed in the previous paragraph as well as an occasional southern red oak (*Quercus falcata*) and chestnut oak (*Quercus montana*). The hickory group consisted of pignut and mockernut hickory. The miscellaneous group was comprised of several species (dogwood, blackgum, sourwood, and serviceberry) that are primarily limited to the midstory stratum of mature stands. Stump sprouts arising from the same root system were tallied as one stem. Also in each plot, a stem of each group visually judged to represent the average height of that group was permanently tagged. Each representative stem was measured for height to the nearest centimeter. Preburn stem tallies and measurements were collected in fall 1994.

**Table 1**
Environmental conditions and behavior of seasonal prescribed fires conducted in three oak shelterwood stands in central Virginia, USA.

| Conditions | Dunnavant | Lake Road | Ward Farm |
|---|---|---|---|
| Winter burn | | | |
| Date | 25 February 1995 | 27 February 1995 | 27 February 1995 |
| Time of burn | 13:00 | 11:00 | 14:30 |
| Air temperature (°C) | 8 | 6 | 9 |
| Relative humidity (%) | 26 | 62 | 54 |
| Wind direction | Northwest | East | East |
| Wind speed (km/h) | 6 | 3 | 4 |
| Cloud cover (%) | 0 | 100 | 100 |
| Fuel moisture (%)[a] | 10 | 15 | 15 |
| Flame length (m) | 0.7 | 0.2 | 0.4 |
| Rate-of-spread (m/min) | 1.4 | 0.4 | 0.4 |
| Spring burn | | | |
| Date | 26 April 1995 | 26 April 1995 | 26 April 1995 |
| Time of burn | 20:00 | 16:30 | 18:30 |
| Air temperature (°C) | 20 | 23 | 21 |
| Relative humidity (%) | 28 | 20 | 20 |
| Wind direction | Southwest | Southwest | Southwest |
| Wind speed (km/h) | 2 | 8 | 5 |
| Cloud cover (%) | 0 | 0 | 0 |
| Fuel moisture (%)[a] | 10 | 10 | 10 |
| Flame length (m) | 0.6 | 1.3 | 0.8 |
| Rate-of-spread (m/min) | 0.6 | 2.5 | 0.8 |
| Summer burn | | | |
| Date | 24 August 1995 | 24 August 1995 | 24 August 1995 |
| Time of burn | 16:30 | 14:30 | 12:30 |
| Air temperature (°C) | 33 | 35 | 35 |
| Relative humidity (%) | 56 | 44 | 44 |
| Wind direction | Southwest | Southwest | Southwest |
| Wind speed (km/h) | 1 | 8 | 6 |
| Cloud cover (%) | 0 | 0 | 0 |
| Fuel moisture (%)[a] | 14 | 14 | 14 |
| Flame length (m) | 0.2 | 0.8 | 0.8 |
| Rate-of-spread (m/min) | 1.2 | 1.5 | 1.2 |

[a] Moisture of downed woody debris between 0.64 and 2.54 cm diameter.

The 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 (Table 1). The spring fires occurred when leaves of the red maple and yellow-poplar regeneration were 50–75% expanded. All prescribed fires were ignited with drip torches in a strip-head fire pattern commencing at the downwind side of the treatment area. Ignition strips were initially spaced 3 m apart and gradually widened to 15 m once firelines were secured. Overall, the prescribed fires were easily executed.

During each burn, fire behavior and characteristics were monitored using four methods. Flame length was estimated by photographing the flaming front passing by residual trees (five per burn unit) whose lower boles were marked with paint in 0.3-m intervals to a height of 2 m (Rothermel and Deeming, 1980). Rate-of-spread was calculated by marking, timing, and measuring five 2-min runs per burn unit with a stopwatch. Fire temperature was measured in each plot by placing two ceramic tiles marked with heat-sensitive paint (40–260 °C in 20 °C intervals) on the outer edge of the plot, opposite each other, at 1 m height, and facing toward plot center. Depending on fire intensity, some of the paints melted as the fire passed through the plot, providing an estimate of the maximum temperature reached in each plot. Finally, each plot was photographed before the fires and fuel consumption in each plot was estimated by comparing the postburn appearance immediately after the fires to the preburn photograph.

Fire behavior varied among and within each of the seasonal burns (Table 1). In general, the spring fires produced the most intense fire behavior with flame lengths and rates-of-spread averaging 0.9 m and 1.3 m/min, respectively. Winter and summer burns were noticeably less intense than spring burns due to increases in relative humidity and decreases in wind speed. Winter burns had average flame lengths of 0.4 m and rates-of-spread of 0.7 m/min. while flame lengths and rates-of-spread in the summer burns averaged 0.6 m and 1.0 m/min, respectively. Within each seasonal fire, flame lengths typically ranged from a few centimeters to more than 3 m while rates-of-spread ranged from less than 0.1 m/min to more than 5 m/min. Fuel consumption and fire impact within the sampling plots ranged from plots that had incomplete combustion of leaf litter and less than 75% topkill of the regeneration to plots where fuels larger than 3 cm diameter were completely consumed and mature overstory trees were killed.

Measuring fire temperatures and evaluating fuel consumption immediately after the fires with the preburn photograph permitted placement of each burn plot into one of four fire intensity classes. Low-intensity fire was characterized by partial consumption of the fine fuels (leaf litter and woody debris less than 0.6 cm diameter), average temperatures less than 65 °C, and less than 75% top-kill of hardwood regeneration. Medium-low fire intensity had complete burning of fine fuels, temperatures between 65 and 135 °C, and 75–100% top-kill of hardwood regeneration. Medium-high-intensity fire had noticeable reduction of woody fuels between 2.5 and 7.5 cm diameter, average temperatures between 135 and 200 °C, some midstory tree mortality, bark scorch on overstory trees, and 100% top-kill of hardwood regeneration. High-intensity fire was indicated by partial consumption of woody fuels larger than 7.5 cm diameter, average temperatures greater than 200 °C, frequent midstory mortality, and occasional overstory mortality. Assignment of plots to the fire intensity classes resulted in sample sizes of 2–5 plots per class in each burn unit and 10–15 plots per season-of-burn.

Postburn counts and measures of hardwood regeneration were conducted in all treatments in fall 1995 and 1996. However, many stems, especially hickory and oak, in the summer burn did not

**Table 2**
Mean densities (stems/ha ± 1 s.e., $n = 3$) of hardwood regeneration before seasonal prescribed fires (1994), 2-year postfire (1997), and 11-year postfire (2007). Means followed by different uppercase letters are different within that row. Means followed by different lowercase letters are different for that species within that sampling period. Means followed by a plus (+) or minus (−) are greater than or less than the corresponding species/treatment mean for 1994. Alpha is 0.05 for all comparisons.

| Treatment | Hickory | Oak | Red maple | Yellow-poplar | Misc. spp. |
|---|---|---|---|---|---|
| Preburn | | | | | |
| Control | 1900 ± 210Ba | 1578 ± 163Bb | 4478 ± 699Aa | 5572 ± 996Ab | 6000 ± 850Ab |
| Spring burn | 2267 ± 240Ca | 2376 ± 263Cab | 4463 ± 415Ba | 5901 ± 800ABb | 7615 ± 841Aa |
| Summer burn | 1934 ± 215Ca | 3038 ± 543Ca | 3144 ± 484Cb | 9957 ± 962Aa | 5548 ± 762Bb |
| Winter burn | 1811 ± 247Da | 1771 ± 185Db | 3800 ± 306Cab | 7311 ± 973Ab | 5352 ± 647Bb |
| 2-Year postburn | | | | | |
| Control | 1645 ± 235Ca | 1428 ± 254Cb | 4411 ± 504Ba | 5555 ± 911Aa | 5632 ± 836Ab |
| Spring burn | 2090 ± 217Ca | 3367 ± **516Ba+** | 2455 ± **415Cb**− | 2097 ± **442Cc**− | 6972 ± 850Aa |
| Summer burn | 1338 ± 230Ca | 2880 ± 380Ba | 1690 ± **257Cb**− | 2724 ± **600Bb**− | 3698 ± 378Ac |
| Winter burn | 1988 ± 347Ca | 2957 ± **168Ba+** | 2811 ± **311Bb**− | 3216 ± **469Bbc**− | 4831 ± 393Abc |
| 11-Year postburn | | | | | |
| Control | 1455 ± 221Ba | 1238 ± 205Bb | 3773 ± 435Aa | 4350 ± 449Aa | 4477 ± 438Aa |
| Spring burn | 2461 ± 388Ca | 4710 ± **353Ba+** | 2194 ± **342Cb**− | 2194 ± **306Cb**− | 5726 ± 429Aa |
| Summer burn | 2194 ± 235Ca | 4120 ± **328Ba+** | 1873 ± **253Cb**− | 1231 ± **110Cb**− | 5405 ± 418Aa |
| Winter burn | 2462 ± 380Ba | 2465 ± **300Bb+** | 2569 ± **311Bb**− | 2407 ± **212Bb**− | 4517 ± 463Aa |

sprout until 1996, so the 1995 summer burn data were ignored and 1996 was considered the first postburn inventory. Plots in the summer burn treatment were re-inventoried in 1997 to provide the second-year dataset. In early spring 2006 (11-year postburn), the plots in the control, spring burn, and winter burn treatments were found and the saplings were tallied by the same species groups. Re-measuring the heights of the tagged representative stems in each plot was not possible because many had died or simply could not be found so the saplings were tallied by three broad height classes (1.5–3.0 m, 3.1–4.5 m, and greater than 4.5 m). The summer burn plots were found and tallied in early spring 2007. Of the 180 plots in this study, only 4 (all control plots) could not be found.

Also during the 11th-year inventory, each plot was designated as dominated by hickory, oak, red maple, or yellow-poplar based on the tallest stem on the plot. Occasionally, a plot would have two dominant stems of different species. When this happened, the species that would grow the tallest (yellow-poplar > oak > hickory > red maple, Olson and Della-Bianca, 1959) was selected. The origin (seedling, seedling sprout, or stump sprout) of these dominant stems was recorded.

### 2.3. Statistical analysis

The density and height of the hardwood regeneration were analyzed using a randomized complete block with repeated measures via Proc GLM (SAS Institute, 2002). Season-of-burn and species were the treatment effects in the model while stand was the blocking factor and year was the repeated effect. Comparisons of regeneration density and height among and within season-of-burn, species, and year were by Tukey's procedure (Day and Quinn, 1989). Residuals were examined to ensure that model assumptions were met. All comparisons were evaluated at alpha equal to 0.05.

The designation of a dominant species for each plot created a 4 × 4 contingency table for each season-of-burn consisting of the four species groups and four fire intensity classes. To include lack of fire in my analysis of plot dominance, the contingency table was enlarged to 4 × 5 by adding a fifth fire intensity class to each season-of-burn by randomly selecting 1/3 of the control plots and assigning them to the fire treatment as unburned. Chi-square analysis (Zar, 1999) was used to test whether the number of dominant stems in each season-of-burn was evenly distributed among the fire intensity × species groups combinations. All comparisons were evaluated at alpha equal to 0.05.

## 3. Results

At the beginning of the study, densities, heights, and stocking of hardwood regeneration were consistent among species groups, regardless of treatment (Tables 2–4). Generally, yellow-poplar or miscellaneous midstory hardwoods were the most

**Table 3**
Mean heights (m ± 1 s.e., $n = 3$) of hardwood regeneration stems before seasonal prescribed fires (1994), 2-year postfire (1997), and 11-year postfire (2007). Means followed by different uppercase letters are different within that row. Means followed by different lowercase letters are different for that species within that sampling period. Means followed by a plus (+) are greater than the corresponding species/treatment mean for 1997. Alpha is 0.05 for all comparisons.

| Treatment | Hickory | Oak | Red maple | Yellow-poplar | Misc. spp. |
|---|---|---|---|---|---|
| Preburn | | | | | |
| Control | 0.9 ± 0.2Bab | 0.8 ± 0.1Ba | 1.1 ± 0.1Ac | 1.2 ± 0.2Ac | 0.9 ± 0.1Bb |
| Spring burn | 1.1 ± 0.1Bab | 1.2 ± 0.2Ba | 1.6 ± 0.1Ab | 1.6 ± 0.2Ab | 1.4 ± 0.1Ba |
| Summer burn | 0.7 ± 0.1Bb | 0.9 ± 0.1Ba | 1.6 ± 0.1Ab | 1.6 ± 0.2Ab | 1.3 ± 0.1Ba |
| Winter burn | 1.2 ± 0.2Ba | 1.2 ± 0.2Ba | 1.9 ± 0.1Aa | 2.0 ± 0.2Aa | 1.4 ± 0.1Ba |
| 2-Year postburn | | | | | |
| Control | 1.1 ± 0.2Ca | 1.1 ± 0.1Ca | 1.6 ± 0.1Ba | 2.1 ± 0.2Aa | 1.3 ± 0.1Ba |
| Spring burn | 1.0 ± 0.2Ba | 0.9 ± 0.2Bab | 1.5 ± 0.1Aa | 1.7 ± 0.1Aa | 0.9 ± 0.1Bbc |
| Summer burn | 0.6 ± 0.1Bb | 0.7 ± 0.1ABb | 0.9 ± 0.1Ab | 0.9 ± 0.1Ab | 0.7 ± 0.1ABc |
| Winter burn | 1.1 ± 0.2Ba | 1.1 ± 0.1Ba | 1.8 ± 0.1Aa | 2.1 ± 0.1Aa | 1.1 ± 0.1Bab |
| 11-Year postburn | | | | | |
| Control | 3.5 ± 0.2Aa+ | 3.3 ± 0.2Abc+ | 3.3 ± 0.2Aa+ | 3.4 ± 0.2Abc+ | 3.1 ± 0.2Aab+ |
| Spring burn | 3.3 ± 0.1Aa+ | 3.7 ± 0.2Aab+ | 3.7 ± 0.2Aa+ | 3.6 ± 0.2Ab+ | 3.3 ± 0.2Aa+ |
| Summer burn | 2.9 ± 0.1Ab+ | 3.0 ± 0.2Ac+ | 3.0 ± 0.2Ab+ | 3.0 ± 0.2Ac+ | 2.7 ± 0.1Ab+ |
| Winter burn | 3.6 ± 0.2Ba+ | 3.8 ± 0.2Ba+ | 3.6 ± 0.2Ba+ | 4.4 ± 0.2Aa+ | 2.8 ± 0.1Cb+ |

abundant species groups. Mean densities ranged from 5352 (midstory hardwoods, winter burn) to 9957 stems/ha (yellow-poplar, summer burn). Next most abundant was red maple averaging 3971 stems/ha. Hickory and oak were the least common species groups with average densities ranging between 1578 and 2191 stems/ha. In comparing treatments, oak and yellow-poplar were most abundant in the summer burn while red maple was most common in the control or spring burn. Miscellaneous hardwoods were more abundant in the spring burn area than in any other treatment and hickory was equally abundant in all treatments. Across all treatments, yellow-poplar and red maple were the tallest species groups with an average height of approximately 1.6 m. They were followed in height by midstory hardwoods (1.2 m). Hickory and oak were the two shortest species groups, averaging 1.0 m in height. All species were widespread, stocking ranged from 76 to 100%.

Two years after the seasonal prescribed fires, density relationships among the species groups were unchanged in the control, but altered in the three burn treatments (Table 2). In the control, yellow-poplar and miscellaneous midstory hardwoods were the most abundant (∼5600 stems/ha) followed by red maple (4411 stems/ha) and hickory and oak (1645 and 1428 stems/ha, respectively). However, in the three burn treatments, midstory hardwoods were the most common (3698–6972 stems/ha) followed by oak (2880–3367 stems/ha). Yellow-poplar was just as abundant as oak in the summer and winter burns (2724–3216 stems/ha), but was less plentiful than oak in the spring burn (2097 stems/ha). In the winter burn, red maple was as abundant as oak (2811 stems/ha), but was less plentiful than oak in the spring and summer burns (1690–2455 stems/ha). Hickory (1338–2090 stems/ha) was the least abundant species in all fire treatments. The height relationships among the five species groups in the control treatment were; yellow-poplar was the tallest, hickory and oak were the shortest, and red maple and midstory hardwoods were intermediate (Table 3). In the three fire treatments, heights were similar among the five species groups. Generally, yellow-poplar was the tallest species, however, there was no difference among the other four species groups and in some treatments hickory, oak, or red maple was just as tall as the yellow-poplar. Stocking rates varied by species among the treatments (Table 4). Generally, each species had its lowest stocking in the summer burn, 56–80%. Hickory and oak had their highest stocking (91–96%) in the spring and winter burns while red maple and yellow-poplar had their highest stocking (76–100%) in the control.

Eleven years after the seasonal prescribed fires, density and height relationships among the five species groups largely were similar to those documented two growing seasons after the burns were conducted (Tables 2 and 3). In the control, yellow-poplar, red maple, and midstory hardwoods remained the most abundant (3773–4477 stems/ha) followed by hickory and oak (1455 and 1238 stems/ha, respectively). However, heights among all species groups were equal, approximately 3.3 m. In the spring and summer burns, midstory hardwoods were the most common (5405–5726 stems/ha) followed by oak (4120–4710 stems/ha), and then hickory, red maple, and yellow-poplar (1231–2461 stems/ha). Like the control, heights within the spring and summer burns heights were equal (∼3.5 and 2.9 m, respectively) among the five species groups. In the winter burn, midstory hardwoods were the most abundant (4517 stems/ha) followed by the other four species groups (∼2475 stems/ha). Yellow-poplar was the tallest species (4.4 m) in the winter burn treatment followed by hickory, oak, and maple (3.6–3.8 m) and finally by midstory hardwoods (2.8 m). Among treatments, stems were generally the tallest in the spring and winter burns, shortest in the summer burn, and intermediate in the control, regardless of species. Stocking of the five species groups varied widely in the 11th year (Table 4). In the control, stocking of hickory and oak was 33 and 36%, respectively, while stocking of red maple and yellow-poplar exceeded 90%. The opposite trend was evident in the spring and summer burns. Hickory and oak stocking ranged from 84 to 96% while red maple and yellow-poplar stocking was 47–67%. Stocking rates for the species groups in the winter burn were comparable to each other, 67–100%.

Since the study's inception, the regeneration layer has undergone profound changes (Tables 2–4). Densities of red maple and yellow-poplar decreased in the three burn treatments, but not in the control. Conversely, oak densities increased in the three burn treatments. Densities of hickory have not changed in any of the treatments between preburn levels and those of year 11. In all treatments, the seedlings and sprouts of all species have grown 1–2 m in height. Stocking of hickory and oak in the control decreased from approximately 95% to 33 and 36%, respectively. Red maple and yellow-poplar stocking similarly dropped in the spring and summer burn treatments.

The distribution of the dominant stems in year 11 by origin type (seedling, seedling sprout, stump sprout) varied by species groups and by treatment (Fig. 2). Seedling-origin dominant stems were only found in the control treatment and they were so rare they were combined with seedling sprouts for reporting purposes. Regardless of treatment, at least 50% (usually 63–86%) of all dominant red maple and yellow-poplar stems were stump sprouts. Conversely, 71–89% of the hickory and oak dominant stems came from seedling sprouts in the three burn treatments. Neither of the two dominant hickory and oak saplings in the control originated as a seedling sprouts; both arose from stump sprouts. Regardless of species group and treatment, stump sprouts were always taller than

**Table 4**
Stocking (proportion of plots with at least one stem) of hardwood regeneration prior to seasonal prescribed fires (1994), 2-year postfire (1997), and 11-year postfire (2007).

| Treatment | Hickory | Oak | Red maple | Yellow-poplar | Misc. spp. |
|---|---|---|---|---|---|
| Preburn | | | | | |
| Control | 96 | 93 | 100 | 76 | 100 |
| Spring burn | 93 | 84 | 96 | 89 | 100 |
| Summer burn | 91 | 87 | 100 | 91 | 100 |
| Winter burn | 98 | 93 | 96 | 80 | 100 |
| 2-Year postburn | | | | | |
| Control | 87 | 80 | 100 | 76 | 100 |
| Spring burn | 91 | 93 | 80 | 49 | 100 |
| Summer burn | 76 | 71 | 67 | 56 | 80 |
| Winter burn | 96 | 93 | 93 | 69 | 100 |
| 11-Year postburn | | | | | |
| Control | 33 | 36 | 93 | 75 | 90 |
| Spring burn | 84 | 87 | 53 | 53 | 93 |
| Summer burn | 89 | 96 | 67 | 47 | 90 |
| Winter burn | 91 | 84 | 85 | 67 | 100 |

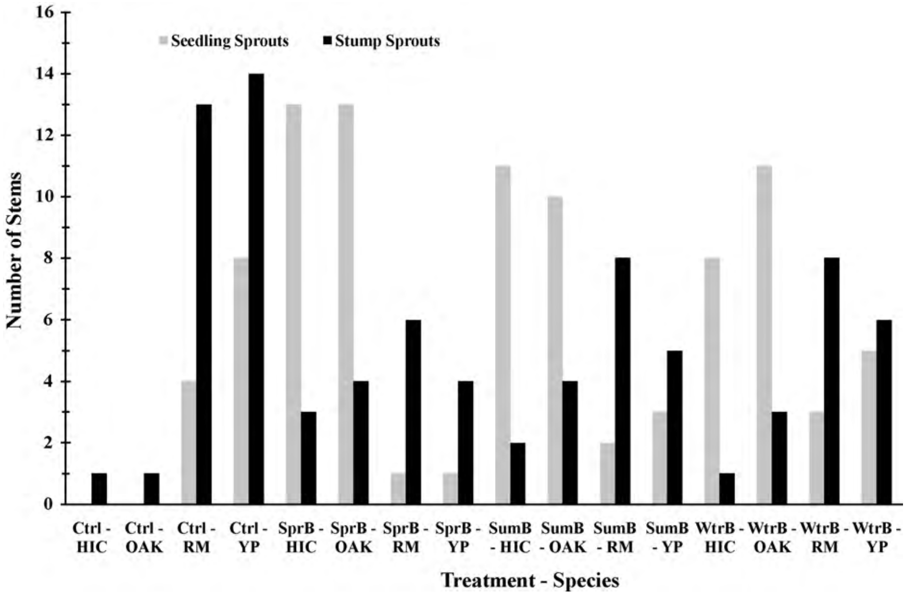

**Fig. 2.** The distribution of the 176 dominant hardwood saplings 11 years after seasonal prescribed fires by origin (seedling sprout or stump sprout), treatment and species. Abbreviations are: Ctrl = control, SprB = spring burn, SumB = summer burn, WtrB = winter burn, HIC = hickory, RM = red maple, and YP = yellow-poplar. Note that most of the red maple and yellow-poplar saplings arose from stump sprouts while hickory and oak saplings originated as seedling sprouts in the three fire treatments.

seedling sprouts (Fig. 3). On average, stump sprouts were twice the height of seedling sprouts.

Analysis of the 4 × 5 contingency table for each fire treatment indicated that the dominant stems were not evenly distributed among the fire intensity classes × species group combinations (Table 5). For each fire treatment, the critical value was 21.03 based on an alpha of 0.05 and 12 degrees of freedom, but the Chi-square values were 31.97, 25.56, and 22.98, respectively, for the spring, summer, and winter burns. Generally, in each of the seasonal fire treatments, the number of dominant hickories and oaks increased and the number of dominant red maples and yellow-poplars decreased as fire intensity increased from none to high. This trend was especially pronounced in the spring burn treatment.

## 4. Discussion

Resource managers and researchers increasingly recognize the historic context and ecological importance of fire in oak forest ecosystems (Yaussy, 2000; Dickinson, 2006; Hutchinson, 2009). However, recognition of an ecological relationship does not necessarily translate into changes in management. Prescribed burning is slowly being integrated into oak forest management partly because of the perception that the changes wrought by fire to the species composition of the hardwood regeneration pool are negative or negligible and ephemeral, and that multiple burns spread over several years are required to produce meaningful changes (Van Lear and Watt, 1993; Brose et al., 2006). Re-inventorying the three oak

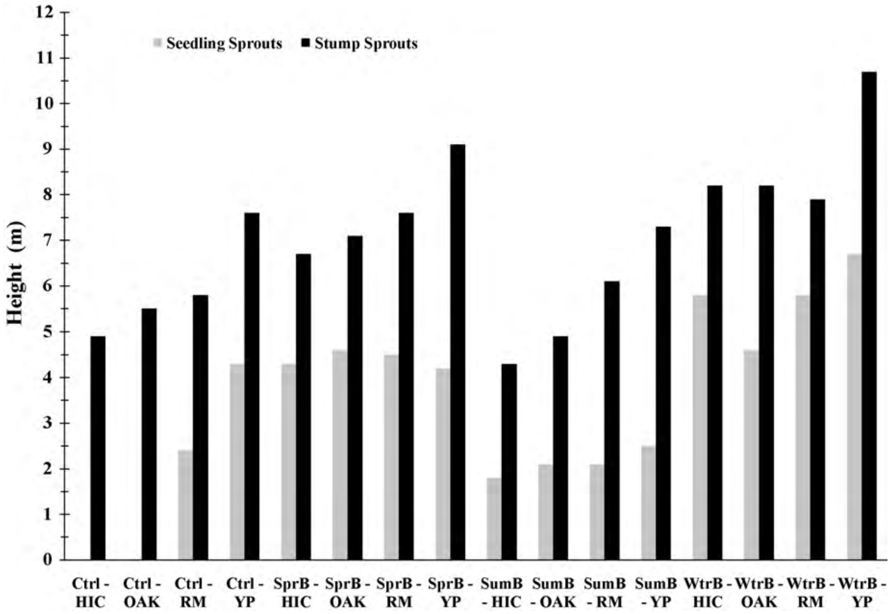

**Fig. 3.** The heights of the 176 dominant hardwood saplings 11 years after seasonal prescribed fires by origin (seedling sprout or stump sprout), species, and treatment. Abbreviations are: Ctrl = control, SprB = spring burn, SumB = summer burn, WtrB = winter burn, HIC = hickory, RM = red maple, and YP = yellow-poplar. Note that the stump sprouts are approximately twice as tall as the seedling sprouts regardless of species or treatment.

**Table 5**
Distribution of the 176 dominant stems in the three seasonal fire treatments by fire intensity class and species group. Number in parentheses are the expected values for each fire intensity class × species group combination. Bold italicized numbers denote the four largest positive and negative departures contributing to the Chi-square value.

| Species | Fire intensity class | | | | | |
|---|---|---|---|---|---|---|
| | No[a] | Low | Medium-low | Medium-high | High | Total |
| Spring burn | | | | | | |
| Hickory | 1 (4.0) | 3 (2.3) | 2 (3.7) | 5 (3.5) | 6 (3.5) | 17 |
| Oak | −***0*** (4.0) | 1 (2.3) | 4 (3.7) | 6 (3.5) | 6 (3.5) | 17 |
| Red maple | ***+6*** (3.1) | 2 (1.8) | 4 (2.9) | 1 (2.6) | −***0*** (2.6) | 13 |
| Yellow-poplar | ***+7*** (2.8) | 2 (1.6) | 3 (2.6) | 0 (2.4) | 0 (2.4) | 12 |
| Total | 14 | 8 | 13 | 12 | 12 | 59 |
| Test statistics: Chi-square = 31.97, critical value = 21.03, alpha = 0.05, degrees of freedom = 12 | | | | | | |
| Summer burn | | | | | | |
| Hickory | −***0*** (3.1) | 3 (2.9) | 3 (3.7) | 3 (1.5) | ***+4*** (1.8) | 13 |
| Oak | −***0*** (3.3) | 4 (3.1) | 5 (4.0) | 2 (1.7) | 3 (1.9) | 14 |
| Red maple | 5 (3.6) | 2 (3.3) | 5 (4.3) | 2 (1.8) | 1 (2.0) | 15 |
| Yellow-poplar | ***+9*** (3.7) | 4 (3.7) | 4 (4.9) | 0 (2.0) | 0 (2.3) | 17 |
| Total | 14 | 13 | 17 | 7 | 8 | 59 |
| Test statistics: Chi-square = 25.56, critical value = 21.03, alpha = 0.05, degrees of freedom = 12 | | | | | | |
| Winter burn | | | | | | |
| Hickory | 0 (2.0) | 1 (2.0) | 3 (2.3) | 2 (1.5) | ***+3*** (1.1) | 9 |
| Oak | 1 (3.4) | 1 (3.4) | 6 (3.9) | 3 (2.6) | ***+4*** (1.8) | 15 |
| Red maple | 6 (3.8) | 5 (3.8) | 3 (4.4) | 3 (2.9) | ***-0*** (2.1) | 17 |
| Yellow-poplar | 6 (3.8) | 6 (3.8) | 3 (4.4) | 2 (2.9) | ***-0*** (2.1) | 17 |
| Total | 13 | 13 | 15 | 10 | 7 | 58 |
| Test statistics: Chi-square = 22.98, critical value = 21.03, alpha = 0.05, degrees of freedom = 12 | | | | | | |

[a] This column contains the dominant stems of randomly selected plots in the unburned control.

shelterwood stands 11 years after the 1995 burns provided the means to explore this perception of disappearing fire effects by testing the predictions made in 1996–1997 regarding the effects of season-of-burn, fire intensity, and their interaction on future stand development (Brose et al., 1999). Overall, the re-inventory shows the initial predictions to be relatively accurate.

Prediction 1 was that yellow-poplar would dominate in the control and all seasonal burns treated with low-intensity fire. That prediction was partially confirmed. Yellow-poplar, along with red maple, clearly dominated the new stand that was developing in the absence of fire. These species outnumbered hickory and oak by about a 3:1 ratio in the controls. Yellow-poplar or red maple was found on nearly every plot while oak and hickory occurred on only a third of the plots. When oak and hickory were present, they were as tall as their competitors, but the limited occurrence of large hickory and oak saplings resulted in red maple or yellow-poplar dominating 39 of the 41 control plots after 11 years. The low-intensity fires differed between spring/summer and winter with the latter quite similar to the unburned controls. In that treatment × fire intensity combination, yellow-poplar and red maple dominated 11 of 13 plots. In the spring and summer low-intensity fires, dominance was more equitable among the species groups with each one dominating approximately 25% of the plots.

Prediction 2 was that red maple and yellow-poplar would dominate spring and winter burns conducted at medium-low intensity. That is not occurring. While these two species are quite prevalent, they are not dominating. After 11 years, approximately 50% of the plots are dominated by yellow-poplar and red maple. The rest are dominated by hickory and oak. The resiliency of hickory and oak in these season-of-burn × fire intensity combinations is likely due to substantial root development before the burns coupled with adequate light to initiate and maintain vigorous height growth (Miller et al., 2004a; Brose, 2008).

Prediction 3 was that there would be no dominant species in areas burned with medium-high spring or winter fire or medium-low summer fire. That certainly seems to be the case for the latter two combinations as they both have nearly equal distributions of dominant stems among the four species groups. However, the medium-high spring fire is trending toward oak and hickory as these species dominate 11 of the 12 plots.

Prediction 4 was that oak would dominate areas that experienced medium-high summer fires or high-intensity fire in any season. At this time, oak is co-dominating these combinations with hickory. Yellow-poplar was often present in the plots, but it never dominates. Likewise, red maple was usually found in the plots, but it dominated only 3 of the 34 plots in these four combinations.

The distribution of the dominant stems by seedling sprout or stump sprout is interesting from several perspectives. It is well known that stump sprouts will outgrow seedlings and seedling sprouts (McQuilkin, 1975; Beck and Hooper, 1986; Palik and Pregitzer, 1993) so it was not surprising that many of the dominant saplings were of stump sprout origin. What is interesting is that was not true for hickory and oak in the three fire treatments. In the three seasonal burns, the majority of the dominant hickories and oaks arose from seedling sprouts, not stump sprouts. The lack of hickory and oak stump sprouts as dominant stems is explained, in part, by the retention of hickory and oak for wildlife purposes during the first shelterwood harvest by the VDGIF. There were only a few hickory and oak stumps to sprout. Also, many of the oaks that were harvested were mature black and white oaks; two species known to produce few, if any, stump sprouts at sizes greater than 30 cm dbh (Sander et al., 1976; Weigel and Chao-Ying, 2002).

However, the abundance of seedling-sprout-origin hickory and oak as dominant stems is also due to the intensity, sequence, and timing of the ice storms, shelterwood harvests, and the fires. The canopies were initially opened by the ice storms in the late 1980s. This canopy disturbance was followed by another, the shelterwood harvests of the early 1990s. Those cuts removed about 50% of the overstory and nearly all the midstory. These initial shelterwood harvests were heavier than what is usually done in oak forests, but the postharvest light levels facilitated rapid development of the oak and hickory root systems (Brose, 2008). Then there was a 4-year interval between the harvests and the fires. This lull also promoted root development of the oak and hickory regeneration (Brose, 2008). So by the time of the fires in 1995, the hickory and oak seedlings would have had at least 4 years of increased understory light to grow large roots. This enhanced root development translated into high postfire sprouting rates and vigorous height growth that resulted in dominant hickory and oak saplings. A less intense harvest or not waiting as long to burn would have resulted in less oak and hickory root development and poorer survival and growth (Brose and Van Lear, 2004; Brose, 2008).

The abundance of stump sprouts as dominant red maple and yellow-poplar saplings also reflects the shelterwood harvests. Those cuts preferentially removed those two species, creating an abundance of stump sprouts. The fires killed nearly all stems in the regeneration layer and forced them to sprout. The original red maple and yellow-poplar stump sprouts were killed by the fire, but rapidly replaced by new sprouts that vigorously grew into dominant saplings while the seedlings of these two species that did sprout postfire apparently lacked sustained vigorous growth resulting in only a small percentage of them becoming dominant stems. In other words, fire has a much stronger impact on red maple and yellow-poplar seedlings than it does on their stump sprouts. Generally speaking, these species groups and origin types are roughly distributed in postfire survival and vigor as stump sprouts (all species) > hickory and oak seedling sprouts > red maple and yellow-poplar seedlings.

The abundance of red maple and yellow-poplar stump sprouts as dominant stems also highlights the need of chemically treating large, undesirable stems before harvesting (Loftis, 2009) or doing so to freshly-cut stumps to minimize sprouting or controlling the stump sprouts postfire to prevent their dominance of the new stand. Herbicides are superior to fire when it comes to controlling large stems or stump sprouts.

The increasing oak dominance and decreasing red maple and yellow-poplar dominance as season-of-burn changes from dormant to growing season and fire intensity increases from low to high is a function of their silvical characteristics. Acorns that survive to become seedlings were often buried by wildlife and their germination is hypogeal (Sander, 1990). These two traits result in their root collars and accompanying dormant buds being below the soil surface where they are protected from fire. Early growth emphasizes root development in lieu of stem growth. Red maple and yellow-poplar seeds are not buried by wildlife and their germination is epigeal (Beck, 1990; Walters and Yawney, 1990). Consequently, their root collars and basal buds are at or above the soil surface and exposed to fire. They emphasize height growth, not root development. These fundamental differences are manifested as differential survival rates when the regeneration is killed by fire. Mortality rates of oak range from 10 to 50%, depending on season-of-burn and fire intensity while those of red maple and yellow-poplar are 13–74% and 54–90%, respectively (Brose and Van Lear, 1998, 2004). Consequently, some lighter intensity fires or not burning lead to yellow-poplar or red maple dominance because only a small proportion of these species fail to sprout postfire and those that do grow faster than oak (Brose et al., 1999). Conversely, a much larger proportion of yellow-poplar and red maple fail to sprout after high-intensity spring fire, resulting in oak and hickory winning the growing space (Brose et al., 1999; Brose and Van Lear, 2004). Whether oak or its competitors dominate after a fire depends, in part, on when and where that fire occurs along the season-intensity gradients.

The strong positive response of hickory to the fire treatments was not unexpected because this genus has many silvical characteristics in common with oak (Smith, 1990). Before the fires, hickory regeneration was the least abundant and shortest of the four species groups. It sprouted postfire at about 85% in the spring and winter burns and 43% in the summer burn (Brose and Van Lear, 1998). Second-year height was on par with that of the other species groups. After 11 years, hickory is as common and as tall as red maple and yellow-poplar in the three burn treatments. More importantly, hickory dominates 38 of 135 burn plots, but only 1 of 41 control plots. Apparently, hickory responds just as well as oak to fire in shelterwood stands.

There is another factor of the shelterwood affecting the data in this study that merits mentioning because of its management implications. The final harvest has yet to occur. Normally, the final harvest of a two-cut shelterwood sequence occurs within a few years of the first harvest. The extended retention of the overstory has probably reduced the height growth of yellow-poplar (Miller et al., 2004b, 2006). Had the canopy been removed, the surviving yellow-poplar would have likely dominated throughout the treatments and erased the benefits of the fires for the oaks. The effects of varying the time between the initial and final harvest of a 2-cut shelterwood sequence on the regeneration pool is an area needing research.

Whether the benefits resulting from the seasonal fires to the hickory and oak components of these stands continue through their development to maturity is not clear. These stands are on medium- to high-quality sites capable of growing large yellow-poplar so that species may yet dominate these new stands (Olson and Della-Bianca, 1959; Kolb et al., 1990). Even though hickory and oak dominated 83 of 135 (61%) burn plots, often there was a tall yellow-poplar located just outside the plot boundary that may yet occupy that growing space as the stand develops. Also, future disturbances may push the stands towards oak/hickory or yellow-poplar/red maple depending on the exact nature of the disturbance. For example, ice or wind storms may preferentially damage dominant yellow-poplars and release co-dominant and intermediate oaks. Conversely, if gypsy moth (*Lymantria dispar*) invades the stands, oaks will be negatively impacted because their foliage is a preferred food of the caterpillars.

What is clear is that fire in shelterwood stands can benefit oak and hickory regeneration for at least a decade, especially if the burning is done in the spring during leaf expansion and at medium to high-intensities. This finding has important management implications because crown closure occurs between ages 10 and 15 in new even-aged stands and at that time crop tree management can begin (Miller, 2000; Miller et al., 2007; Brose et al., 2008). These stands could easily be pushed toward almost certain oak dominance in the future by selecting approximately 120 high-quality oak saplings per hectare at this time and giving each a crown-touching release (Miller et al., 2007; Brose et al., 2008). Past and recent research shows that sapling oaks managed as crop trees have almost a 100% survival rate to maturity if they are in a dominant canopy position at crown closure (Ward and Stephens, 1994; Ward, 2009).

Based on the results of this study, fire during the initiation phase of a new stand can have a profound, long-lasting benefit for oak regeneration and using fire in conjunction with shelterwood harvesting and followed by crop tree management is probably the best approach to sustaining oak forest ecosystems into the future.

## Acknowledgements

This research was possible due to the assistance of many individuals both in the 1990s as well as more recently. Special thanks are owed to retired professor David Van Lear of Clemson University who served as my major advisor during the study's initial phase from 1994 to 1997. I am indebted to the Virginia Department of Game and Inland Fisheries, especially former wildlife biologist Patrick Keyser, for providing the study sites, conducting the prescribed fires, and providing many other forms of technical assistance. I also thank the following people from the U.S. Forest Service–Northern Research Station for their assistance: Josh Hanson, Lance Meyen, and Greg Sanford for collecting the sapling data in 2006 and 2007, John Stanovick for statistical guidance, and Gary Miller and Daniel Yaussy for reviewing earlier drafts of this manuscript. Finally, Northern Research Station Unit 02 is thanked for funding the second round of data collection and manuscript preparation.

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