Forest Ecology and Management 255 (2008) 3374–3381

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Full length article

Root development of acorn-origin oak seedlings in shelterwood stands on the Appalachian Plateau of northern Pennsylvania: 4-year results

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ARTICLE INFO

Article history:
Received 26 October 2007
Received in revised form 14 February 2008
Accepted 18 February 2008

Keywords:
Quercus
Shelterwood
Root collar diameter
Prescribed fire

ABSTRACT

Post-fire sprouting of oak seedlings in prescribe-burned shelterwood stands hinges on their root collar diameters exceeding 6.4 mm and root size depends on the type of partial cut and the time since harvest. To better understand this shelterwood stage/time/oak root size relationship, a study was begun in northern Pennsylvania in 2001. Acorns of black, chestnut, northern red, and white oak (*Quercus velutina*, *Q. montana*, *Q. rubra*, and *Q. alba*, respectively) were planted in mixed-oak stands treated with one of the cuts of a three-step shelterwood sequence (uncut, preparatory cut, first removal cut, and final cut) and the root development of the resultant seedlings was followed for 4 years. Root development of all four oak species was the least in the uncut treatment and changed little after the first year. Only northern red oak showed an increase in root size in the preparatory cut by the fourth year. All oak species had significantly larger roots in the first removal cut and final cut treatments by the fourth year with black and northern red oak having their most root development in the final cut and chestnut and white oak having their most root growth in the first removal cut. All species in the first removal cut and final cut treatments were nearing or had surpassed the 6.4 mm root collar diameter threshold by the third or fourth year indicating that at least 4 or 5 years should pass between the harvest and the prescribed fire.

Published by Elsevier B.V.

1. Introduction

Throughout the hardwood forests of eastern North America, land managers often face considerable difficulty regenerating mixed-oak (*Quercus* spp.) stands, especially on mesic upland sites, i.e., oak site index$_{50}$ > 19 m (Crow, 1988; Loftis and McGee, 1993; Johnson et al., 2002). Many factors contribute to this widespread oak regeneration problem, but dense understory shade is the primary obstacle limiting survival and growth of oak seedlings and sprouts (Loftis, 1983; Lorimer, 1993; Lorimer et al., 1994). Oak stands lacking disturbance for decades often have multiple strata of non-oak vegetation shading the forest floor (McGee, 1984; Abrams and Downs, 1990; Schuler and Gillespie, 2000; Aldrich et al., 2005). In such stands, understory light may be as low as 1–3% of full sunlight (Hutchison and Matt, 1977; Floyd et al., 1978; Lorimer et al., 1994; Miller et al., 2004).

Young upland oaks [black (*Q. velutina*), chestnut (*Q. montana*), northern red (*Quercus rubra*), scarlet (*Q. coccinea*), and white (*Q. alba*)] are intermediate in their sunlight requirements (McQuilken, 1990; Johnson, 1990; Rogers, 1990; Sander, 1990a,b). Shade tolerance ranking of these five species is: white > chest-chestnut > northern red > black > scarlet (Johnson et al., 2002). Most species can survive for several years in as little as 5% of full sunlight (Hanson et al., 1987) but need at least 20% of full sunlight before they can consistently maintain shoot growth (Dickson, 1991; Gottschalk, 1994). Maximum photosynthesis of northern red oak seedlings occurs at about 30% of full sunlight with little increase at higher light levels (Kramer and Decker, 1944; Bourdeau, 1954; Phares, 1971; Kolb et al., 1990). To meet these light requirements, forest managers often use the shelterwood system.

In general terms, the shelterwood system is a series of partial cuts that removes the trees of an existing stand over several years and eventually culminates in a final cut that creates a new even-aged stand (Johnson et al., 2002). On intermediate and mesic sites, many oak stands develop excessive competition from other woody vegetation during this sequence of harvests. When that is likely to occur or has already happened, measures must be taken to control this competition and ensure an oak component in the new stand. Loftis (1990a,b) and Lorimer et al. (1994) demonstrated the value of herbicides in controlling existing woody competition at the start a shelterwood sequence. Prescribed fire can be used during a

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0378-1127/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.foreco.2008.02.021

shelterwood sequence to release oak regeneration from competing vegetation (Brose and Van Lear, 1998; Brose et al., 1999a,b).

The use of fire to release oak regeneration from competing vegetation during a shelterwood sequence can be problematic because survival and post-fire sprouting of oak roots are governed by fire seasonality, fire intensity, root collar location in the soil, and root size. Brose and Van Lear (2004) showed increased survivorship for hardwood roots that attained a root collar diameter (RCD) of at least 6.4 mm and the root collar was located in the Oa soil horizon or deeper. The RCD size criterion begs the questions of (1) what is the optimal shelterwood stage for developing this root size and (2) how much time will roots need to develop to that size? Unfortunately, nearly all oak seedling growth studies in shelterwood stands focus on height growth (Loftis, 1983; Johnson et al., 1989; Schlesinger et al., 1993; Lorimer et al., 1994; Spetich et al., 2002; Lhotka and Loewenstein, 2008). A notable exception to this focus on height is a study by Miller et al. (1994). In that study, basal diameter (a surrogate for RCD) significantly increased over 3 years for small northern red oak seedlings growing in 12% full sun compared to those growing in 2 and 4% full sun.

The purpose of this paper is to report 4-year results of an ongoing study comparing the seedling root development of four upland oak species in the stages of a three-step shelterwood sequence—uncut control, preparatory cut, first removal cut, and final cut (Smith, 1986). Specific hypotheses are:

(1) The stages of a three-step shelterwood sequence will have distinct and unchanging understory light levels.
(2) All oak species will exhibit little, if any, root growth in the uncut control.
(3) For all oak species, the root development relationship among the shelterwood stages will be uncut < preparatory cut < first removal cut = final cut.
(4) By the end of the fourth growing season, differences in root sizes among species will reflect differences in their relative growth rates, i.e., northern red > black = chestnut > white, regardless of shelterwood stage.
(5) All oak species will meet or surpass the 6.4 mm RCD threshold by the end of the fourth growing season in all shelterwood stages except the uncut control.

Understanding the developmental dynamics of oak seedling roots in different shelterwood stages will help foresters prescribe the optimal residual density for their particular circumstances and integrate prescribed fire into a shelterwood sequence so as to ensure maximum sprouting of the advanced oak regeneration.

2. Methods

2.1. Study sites

This study is being conducted at Clear Creek State Forest (CCSF), Elk State Forest (ESF), and Game Land 152 (GL152) in the Appalachian Plateau Province of northern Pennsylvania (Schultz, 1999). These properties are owned and managed by the Pennsylvania Bureau of Forestry and Pennsylvania Game Commission, respectively. Because they are in the same province, these sites share several common characteristics (Table 1). All are on broad, flat hilltops so slope is near zero and aspect is inconsequential. The sites have cool, humid summers and cold, snowy winters. Average annual temperature is 8.0 °C with an average minimum mean of −10.0 °C in January and an average maximum mean of 25.6 °C in July (Zarichansky, 1964; Yaworski et al., 1979; Kopas, 1993). Annual precipitation for the three sites averages 1060 mm of rain and 1840 mm of snow distributed evenly throughout the year. Growing seasons average 122 days. All sites are extensively forested with a mix of oak and northern hardwood tree species.

The three sites differ in a number of characteristics (Table 1). GL152 was glaciated and its soil is a silt loam (Yaworski et al., 1979). Site index$_{50}$ for northern red oak is approximately 27 m. CCSF and ESF were never glaciated (Zarichansky, 1964; Kopas, 1993). Their soils are channery loams. Site index$_{50}$ for northern red oak is approximately 23 m for CSF and 20 m for ESF. Site quality differences are evident in the forest composition. GL152 is dominated by northern red oak growing in association with American beech (*Fagus grandifolia*), sugar maple (*Acer saccharum*), white ash (*Fraxinus americana*) and yellow-poplar (*Liriodendron tulipifera*). Common tree species at CCSF are northern red oak, chestnut oak, white oak, black cherry (*Prunus serotina*), and red maple (*Acer rubrum*). ESF has the same species, but white and chestnut oaks predominate. Black gum (*Nyssa sylvatica*) also is common at ESF.

2.2. Study design and installation

In summer 2001 at each site, four oak stands, each greater than 4 hectares, representing the stages of a three-step shelterwood sequence – uncut, preparatory cut, first removal cut, and final cut – were located based on knowledge of the professional forester responsible for the property, timber sale records, and visual observation. Generally, these stands were within 200 m of each other. Within each stand, four 8 m × 4 m plots were selected for acorn planting based on the plot being suitable for mechanical

Table 1
Climatic, physiographic, and forest composition characteristics of the three *study sites*

Characteristic	Clear Creek State Forest	Game Land 152	Elk State Forest
Location (latitude, longitude)	41°18′26″N, 79°00′29″W	41°50′51″N, 80°13′42″W	41°26′57″N, 78°06′34″W
Glaciated	No	Yes	No
Average temperature (°C)	8.1	8.3	7.5
Temperature range (°C)	−9.4 to 25.1	−9.0 to 27.2	−11.6 to 24.4
Rainfall (mm)	1030	1070	1080
Snowfall (mm)	1010	2370	2140
Growing season (days)	116	140	109
Elevation (m, a.s.l.)	500	300	575
Slope (%)	5	< 5	5–10
Slope position	Upper flat	Upper flat	Upper flat
Aspect (°)	180	225	130
Soil series	DeKalb	Venango	Hazleton
Channery loam	Silt loam	Channery loam	
Soil family	Typic Hapludult	Aeric Fragiaqualf	Typic Hapludult
Site index (m, nro$_{50}$)	23	27	20
Five most dominant canopy species (% of basal area)	Northern red oak, red maple, black cherry white oak chestnut oak	Northern red oak, sugar maple, yellow-poplar white ash, American beech	White oak, chestnut oak, northern red oak, red maple, black gum

tilling, i.e., free of large surface rocks. Basal area was determined with a 10-factor prism from plot center. All trees greater than 2.5 cm diameter at a height of 1.37 m (dbh) that were intercepted by the prism were identified to species and measured for dbh to the nearest 2.5 cm. These data were used to calculate relative density (a measure of stocking) of the trees shading the plot (Marquis et al., 1992). Some chainsaw felling of intermediate and suppressed trees was necessary in the preparatory cut and first removal cut stands to ensure they were reasonably visibly different from each other and the uncut stands.

The uncut stands were fully stocked with intact main canopies, well-developed sub-canopies, and little or no sign of any recent cutting. Basal areas ranged from 31 to 44 m^2/ha, but their relative densities were 101–103%. The preparatory cut stands also had intact main canopies, but the sub-canopies were sparse due to removal (felling, harvesting, and/or herbicide injection) of most of the intermediate and suppressed trees within the preceding year (Fig. 1). The uncut and preparatory cut stands also lacked understory herbaceous vegetation less than 2 m tall due to recent broadcast spraying of a sulfometuron methyl herbicide to control undesirable ferns and grasses. Basal areas ranged from 25 to 31 m^2/ha and the corresponding relative densities were 78–85%. The first removal cut stands were cut during the preceding 2 years. They had a limited sub-canopy and large gaps in the main canopy. The remaining main canopy trees were co-dominant oaks selected for retention so they could increase in volume and value. Basal areas in these stands ranged from 16 to 21 m^2/ha and relative densities averaged 48%. The final cut stands were 1–2 years post-harvest. They were devoid of any canopy cover, except occasional residual trees (average basal area and relative density were 4 m^2/ha and 13%, respectively) retained for aesthetic, diversity, or wildlife considerations. The first removal cut and final cut stands also had widespread, rapidly developing tree regeneration and herbaceous plants. The CCSF and ESF stands were surrounded by 2.3 m high woven wire fence to exclude whitetail deer (*Odocoileus virginianus*). Excessive deer browsing was not considered to be a problem at GL152 and those stands remained unfenced.

In fall 2001, acorns of black, chestnut, northern red, and white oak were collected from single mother trees in northwestern Pennsylvania. Mother trees were isolated mature dominant trees of good form and quality. The acorns were floated to identify and remove unsound seeds. The remaining sound acorns were sorted to remove small and deformed ones and to provide a fairly uniform planting stock.

Also in fall 2001, the plots were raked clear of leaf litter and woody debris and tilled to a depth of 7.5 cm with a 4-hp, front-tine rototiller to loosen the soil and remove small surface rocks and roots. Each plot was randomly assigned to one of the four oak species for acorn planting. In each plot, approximately 384 sound acorns (12/m^2) of the assigned species were planted at a depth of 2.5 cm. Chestnut and white oak acorns were planted in fall 2001 and black and northern red oak acorns were cold stratified in a walk-in refrigerator at 1.5 °C for 6 months and planted in spring 2002. Immediately after planting, each plot was completely covered with wire screen (0.63 cm mesh) to prevent acorn pilferage by small mammals. The screen was held flush to the ground with sod staples and remained in place for 1 year.

By summer 2002, each plot contained at least 350 seedlings. Deer penetrated fences that same summer at the ESF first removal and final cut stands resulting in those plantings being destroyed by browsing. Deer also destroyed the plantings in the unfenced final cut stand at GL152. All these stands were replanted in fall 2002 and protected with additional fencing. Consequently, replanted plots also had at least 350 seedlings, but lagged behind the other plantings by 1 year.

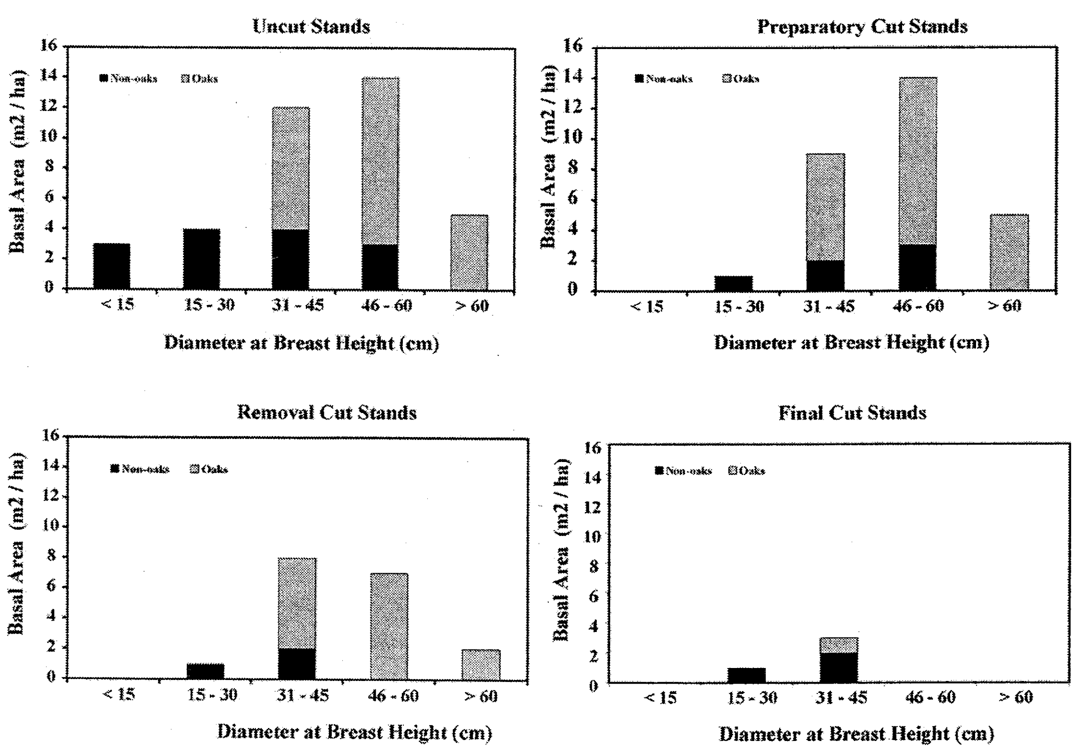

Fig. 1. Structure (basal area by size class) of the four types of oak stands used in the study. Note that oak dominates in total basal area, occupies the largest size classes, and the preparatory and first removal cuts are from below. Oak species are black, chestnut, northern red, scarlet, and white. Non-oaks include a wide suite of species such as American beech, black cherry, eastern hemlock, red maple, sugar maple, and white pine.

2.3. Data collection

Commencing in summer 2002 and annually thereafter, readings were taken in each plot with a ceptometer to measure the proportion of full sunlight reaching the oak seedlings (Parent and Messier, 1996; Gendron et al., 1998). Readings were taken between 11 a.m. and 2 p.m. on uniformly overcast days with the bar of the ceptometer pointing south. Fifteen readings were taken systematically over each planting bed to ensure uniform coverage at a height of approximately 1 m. At the same time, a second light meter was used in fully open conditions to record the maximum ambient light level at 5-s intervals. Both sets of readings were averaged and the two means used to calculate the percent of full sunlight reaching each plot.

Beginning in fall 2002 and annually thereafter, 15 seedlings visually estimated to represent the average height of the cohort were selected in each plot and their entire root systems were excavated from the soil to measure root development. This sample size and protocol was similar to that of previous oak root development studies (Hane, 1999). Each harvested seedling was measured for root collar diameter to the nearest 0.1 mm and taproot length (TL) to the nearest 0.1 cm. Root collar diameter is the junction of the stem and the root and is marked by a ring of callous tissue and dormant buds. After drying at 30 °C to a constant weight, root dry mass (RM) was determined to the nearest 0.1 g using an electronic scale.

Soil compaction data were collected for use as a covariate in the analysis because that factor may influence root development. Beginning in 2002 and annually thereafter, soil compaction (depth in cm to a pressure of 14,065 g/cm^2) was measured in each plot to a maximum depth of 75 cm with a penetrometer. Five readings were made in each plot, at the four corners and the center, and these were averaged to obtain one reading for the plot.

2.4. Statistical analysis

The understory light data were analyzed by growing season as a single-factor analysis of variance (SAS Institute, 2000). Shelterwood stage was the factor and the dependent variable was the average proportion of full sun reaching each plot. An arcsin transformation was performed on the data to correct for unequal variances. Comparisons among shelterwood stages were by Tukey's procedure (Day and Quinn, 1989). For all comparisons, alpha was 0.05.

The root data were analyzed using a repeated measures analysis of variance split-plot design via Proc Mixed (SAS Institute, 2000). Shelterwood stage was the whole-plot unit and oak seedling species was the sub-plot unit. The four shelterwood stages and four oak seedling species were fixed effects in the model and site and site*shelterwood effects were random effects in the model. Growing season was the repeated effect in the model. The dependent variables were RCD, RL, and RM and soil compaction was the covariate. Comparisons among and within main effects and interactions were by Tukey's procedure (Day and Quinn, 1989). Initial model runs revealed that the assumptions regarding normality and homogeneity of variances of the residuals were violated for the RM and TL data. These were subsequently square root transformed and the residuals re-examined to ensure model assumptions were met. For all comparisons, alpha was 0.05.

3. Results

Four distinct understory light regimes were found in the four shelterwood stages at each site (Fig. 2). Understory light in the uncut stands ranged from 3 to 5% of full sun. In the preparatory cut stands, understory light averaged 14.7 ± 0.3% of full sun, a significant increase relative to uncut stands. The first removal cut and final cut stands averaged 48.3 ± 5.1% and 89.3 ± 1.7% of full sun, respectively. These were significantly different from each other and both were substantially more than the understory light levels of the preparatory cut and uncut stands.

Generally, the four shelterwood stages maintained distinct understory light levels during the study (Fig. 2). An exception to this trend occurred in the uncut stands during the second and third growing seasons (2003 and 2004, respectively). In those years, a severe, widespread outbreak of anthracnose occurred because of cool, moist spring weather. This outbreak defoliated the chestnut oaks, white oaks, and red maples in the uncut stands and significantly increased understory light to approximately 17% full sun; a level comparable to the preparatory cut stands. By the fourth growing season (2005), the canopies in the uncut stands had recovered and the understory light regime returned to approximately 5% full sun. There was little or no defoliation observed in the other three shelterwood stages and their understory light levels remained distinctly different from each other.

After adjusting for differences in soil compaction among the 48 plots, significant differences were found for each of the dependent

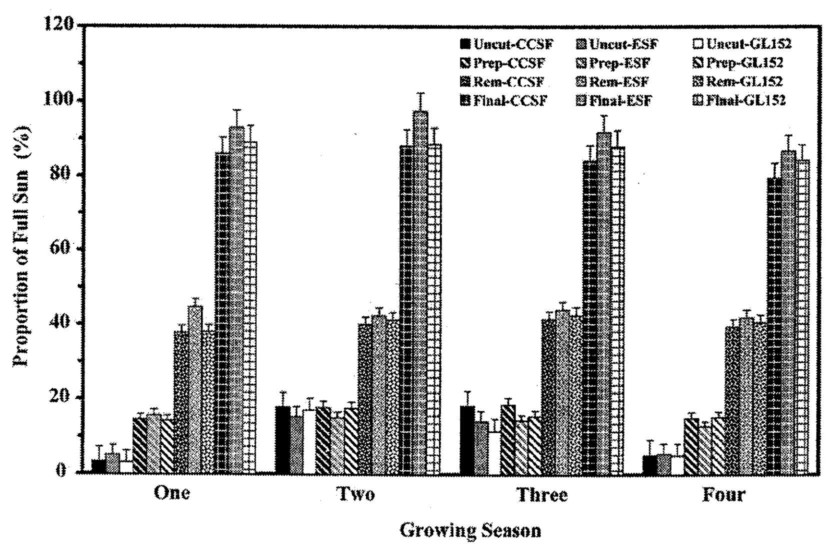

Fig. 2. The average understory light levels of the uncut, preparatory cut, first removal cut, and final cut shelterwood stands at Clear Creek State Forest (CCSF), Elk State Forest (ESF), and Game Lands 152 (GL152) through four growing seasons. The error bars on top of each vertical bar denote one standard error.

Table 2
Adjusted mean root collar diameters (mm ± 1 S.E.) of black, chestnut, northern red, and white oak seedlings growing for 4 years in shelterwood stands in northern Pennsylvania

Growing season	Uncut	Shelterwood stage		Final cut
		Preparatory cut	1st removal cut	
Black oak				
First	3.7 ± 0.62Ba	3.3 ± 0.64Ba	3.8 ± 0.68Bb	5.1 ± 0.60Ac
Second	3.6 ± 0.64Ba	3.7 ± 0.73Ba	5.3 ± 0.74Aab	5.7 ± 0.63Abc
Third	3.4 ± 0.71Ca	3.6 ± 0.62BCa	4.8 ± 0.67Bab	***7.0 ± 0.72Ab***
Fourth	3.6 ± 0.66Cax	3.5 ± 0.72Caz	5.7 ± 0.71Baz	***8.6 ± 0.72Aay***
Chestnut oak				
First	4.5 ± 0.72Ba	4.6 ± 0.68Ba	5.0 ± 0.71ABb	6.0 ± 0.60Aab
Second	4.6 ± 0.65Aa	4.7 ± 0.66Aa	5.8 ± 0.76Aab	5.7 ± 0.74Ab
Third	4.8 ± 0.71Ba	4.3 ± 0.71Ba	***6.9 ± 0.65Aa***	6.1 ± 0.74Aab
Fourth	4.7 ± 0.77Bax	4.4 ± 0.72Baz	***7.1 ± 0.71Aayz***	***7.0 ± 0.66Aaz***
Northern red oak				
First	4.3 ± 0.71Ba	4.4 ± 0.64Bb	5.8 ± 0.62Ab	6.2 ± 0.65Ac
Second	4.2 ± 0.66Ba	4.9 ± 0.76Bab	***6.5 ± 0.72Ab***	***8.0 ± 0.70Ab***
Third	4.3 ± 0.66Ca	5.1 ± 0.75Cab	***6.6 ± 0.72Bb***	***8.4 ± 0.76Ab***
Fourth	4.2 ± 0.64Dax	5.7 ± 0.61Cay	***8.1 ± 0.71Bay***	***11.2 ± 0.78Aax***
White oak				
First	3.9 ± 0.67Aa	3.8 ± 0.68Aa	4.2 ± 0.70Ab	5.2 ± 0.78Ab
Second	4.1 ± 0.73Ba	3.7 ± 0.66Ba	4.6 ± 0.73Bab	6.2 ± 0.74Aab
Third	3.7 ± 0.73Ba	3.8 ± 0.65Ba	5.7 ± 0.81Aa	5.9 ± 0.73Aab
Fourth	*4.2 ± 0.71Bax*	*3.7 ± 0.70Baz*	*5.8 ± 0.80Aaz*	***6.7 ± 0.72Aaz***

Uppercase letters denote differences within that row while lowercase letters denote difference within that shelterwood stage and species. Italicized lowercase letters denote differences among species within that shelterwood stage in the fourth growing season. Alpha is 0.05 for all comparisons and sample size is 40–45 for all species/shelterwood stage/growing season combinations. Bolded italicized means meet or surpass the 6.4 mm threshold for surviving prescribed fires.

Table 3
Adjusted mean taproot length (cm ± 1 S.E.) of black, chestnut, northern red, and white oak seedlings growing for 4 years in shelterwood stands in northern Pennsylvania

Growing season	Uncut	Shelterwood stage		Final cut
		Preparatory cut	1st removal cut	
Black oak				
First	18.5 ± 2.0Ba	20.0 ± 2.1ABb	22.8 ± 2.2ABc	23.2 ± 2.0Ac
Second	19.2 ± 2.0Ba	19.8 ± 2.0Bb	28.0 ± 2.1Ab	24.0 ± 2.0Ac
Third	19.5 ± 2.1Ca	21.0 ± 2.1Cb	28.3 ± 2.0Bb	33.9 ± 2.0Ab
Fourth	21.6 ± 2.1Daz	27.2 ± 2.1Cay	34.1 ± 2.1Bax	40.0 ± 2.1Aay
Chestnut oak				
First	17.1 ± 2.1Ba	18.4 ± 2.1Bb	19.5 ± 2.0ABc	23.1 ± 2.0Ab
Second	17.7 ± 2.1Ca	21.4 ± 2.1BCb	22.2 ± 2.0ABb	23.0 ± 2.1Ab
Third	20.3 ± 2.1Ba	21.5 ± 2.1ABb	23.2 ± 2.1ABb	24.8 ± 2.0Ab
Fourth	20.8 ± 2.1Caz	25.2 ± 2.1Bay	33.1 ± 2.2Aax	30.8 ± 2.1Aaz
Northern red oak				
First	19.5 ± 2.2Ca	21.0 ± 2.0BCb	23.1 ± 2.1ABc	25.1 ± 2.0Ac
Second	20.8 ± 2.0Ca	21.5 ± 2.0Cab	26.3 ± 2.1Bbc	31.7 ± 2.1Ab
Third	21.0 ± 2.1Ba	21.9 ± 2.0Bab	30.2 ± 2.0Aab	33.3 ± 2.1Ab
Fourth	20.4 ± 2.0Daz	24.7 ± 1.9Cay	33.4 ± 2.0Bax	38.8 ± 2.1Aay
White oak				
First	17.1 ± 2.0Ba	17.0 ± 2.0Ba	20.6 ± 2.0Ac	23.0 ± 2.2Ab
Second	17.0 ± 2.0Ba	18.4 ± 2.0Ba	25.1 ± 2.0Ab	26.6 ± 2.3Ab
Third	17.5 ± 2.0Ca	18.2 ± 2.0Ca	27.2 ± 2.0Bb	32.4 ± 2.3Aa
Fourth	*17.9 ± 1.9Baz*	*19.4 ± 1.9Baz*	*31.1 ± 1.9Aax*	*32.5 ± 2.0Aaz*

Uppercase letters denote differences within that row while lowercase letters denote difference within that shelterwood stage and species. Italicized lowercase letters denote differences among species within that shelterwood stage in the fourth growing season. Alpha is 0.05 for all comparisons and sample size is 40–45 for all species/shelterwood stage/growing season combinations.

variables among the four shelterwood stages, the four oak species, the four growing seasons, and their interactions. The shelterwood stages formed two distinct groups (uncut/preparatory cut and first removal/final cut) based on similarity of RCD (Table 2). The first group always contained the smallest RCD while the second group always had the largest RCD, regardless of species or growing season. These two groups differed in RCD in 11 of the 16 species/growing season combinations. When they did not differ, it was usually because of similarity in RCD between the first removal cut and preparatory cut in the first or second growing season. Between the uncut and preparatory cut treatments, RCD never differed for black, chestnut, and white oak, regardless of growing season and only differed for northern red oak after the fourth growing season. The first removal and final cut treatments differed in RCD in 7 of the 16 species/growing season combinations and did not differ in the other nine.

Growing seasons differed in RCD, depending on shelterwood stage and species (Table 2). In the uncut and preparatory cut stages, RCD never differed among growing seasons for black, chestnut, and white oak and only differed for northern red oak in the fourth growing season. In the first removal cut and final cut treatments, all species showed significantly larger RCD by the end of the third or fourth growing season.

By the end of the fourth growing season, there were no differences in RCD among species in the uncut treatment (Table 2). In the other three shelterwood stages, northern red oak always had the largest RCD while black and/or white oak had the smallest RCD. Generally, chestnut oak RCD was intermediate relative to these other species in these three treatments.

The four shelterwood stages formed two groups (uncut/preparatory cut and first removal/final cut) based on similarity of TL (Table 3). The first group always had the shortest TL and the second group always contained the longest TL, regardless of species and growing season. In 11 of the 16 species/growing season combinations these two groups were distinctly different in TL; in the other five there was overlap in TL between the preparatory cut and the first removal cut. Between the uncut and preparatory cut treatments, TL was longest in the preparatory cut for black, chestnut, and northern red oak after the fourth growing season. Otherwise there was no difference between these two shelterwood stages, regardless of species and growing season. There was little difference in TL between the first removal and final cuts. When there was, the final cut always had the longer TL.

TL varied among growing season depending on shelterwood stage and species (Table 3). There were no differences in TL among growing seasons in the uncut treatment, irrespective of species. In the other shelterwood stages, all species had the shortest and longest TL in the first and fourth growing season, respectively. The second and third growing seasons were intermediate in TL; sometimes equivalent to the first or fourth growing season or different from both.

By the end of the fourth growing season, black and northern red oak generally had longer TL than chestnut and white oak, regardless of shelterwood stage (Table 3). The one exception to this trend was in the first removal cut where chestnut oak TL was comparable to that of black and northern red oak.

For RM, the four shelterwood stages formed two groups (uncut/preparatory cut and first removal/final cut) with the smallest RM in the former and the largest RM in the latter (Table 4). However, because of variability, these two groups were only distinctly different in 4 of the 16 species/growing season combinations. Otherwise, there were no differences among shelterwood stages or mixed differences, i.e., first removal cut RM larger than uncut RM but not different from preparatory cut RM. There was a trend of increasing difference between the two groups as they diverged in RM from the first to the fourth growing season for each species. Between the uncut and preparatory cut treatments, there were no differences in RM regardless of growing season and species. The

Table 4
Adjusted mean root mass (g ± 1 S.E.) of black, chestnut, northern red, and white oak seedlings growing for 4 years in shelterwood stands in northern Pennsylvania

Growing season	Uncut	Shelterwood stage		Final cut
		Preparatory cut	1st removal cut	
Black oak				
First	1.4 ± 1.61Aa	1.6 ± 1.68Aa	1.8 ± 1.73Ab	1.6 ± 1.61Ac
Second	1.6 ± 1.63Aa	1.5 ± 1.66Aa	2.4 ± 1.70Ab	3.3 ± 1.63Ac
Third	1.5 ± 1.69Ba	1.6 ± 1.69Ba	2.8 ± 1.86Bb	9.2 ± 1.65Ab
Fourth	1.8 ± 1.70Caz	1.6 ± 1.80Caz	8.7 ± 1.86Baz	21.1 ± 1.88Aay
Chestnut oak				
First	2.5 ± 1.67Aa	2.8 ± 1.70Aa	3.2 ± 1.69Ab	2.9 ± 1.66Ab
Second	2.9 ± 1.67Aa	3.4 ± 1.68Aa	3.3 ± 1.67Ab	3.0 ± 1.71Ab
Third	3.1 ± 1.69Ba	3.3 ± 1.69Ba	3.0 ± 1.66Bb	5.9 ± 1.70Ab
Fourth	3.4 ± 1.72Caz	3.1 ± 1.73Cay	12.2 ± 1.71Aay	8.3 ± 1.71Baz
Northern red oak				
First	2.6 ± 1.75Aa	2.6 ± 1.68Aa	2.5 ± 1.66Ab	4.3 ± 1.90Ac
Second	2.7 ± 1.70Ba	2.9 ± 1.69ABa	3.3 ± 1.66ABb	6.6 ± 1.90Ac
Third	2.3 ± 1.68Ba	3.4 ± 1.70Ba	5.2 ± 1.80Bb	12.6 ± 1.81Ab
Fourth	2.5 ± 1.63Caz	3.5 ± 1.72Cay	13.3 ± 1.80Bay	23.4 ± 1.91Aay
White oak				
First	1.4 ± 1.61Aa	1.5 ± 1.61Aa	2.3 ± 1.80Ab	2.5 ± 1.74Ab
Second	1.6 ± 1.81Aa	1.7 ± 1.73Aa	3.5 ± 1.62Ab	3.9 ± 1.65Ab
Third	2.1 ± 1.77Ba	2.0 ± 1.62Ba	4.0 ± 1.53ABb	5.5 ± 1.63Ab
Fourth	2.0 ± 1.54Baz	2.1 ± 1.58Baz	8.0 ± 1.75Aaz	8.9 ± 1.60Aaz

Uppercase letters denote differences within that row while lowercase letters denote difference within that shelterwood stage and species. Italicized lowercase letters denote differences among species within that shelterwood stage in the fourth growing season. Alpha is 0.05 for all comparisons and sample size is 40–45 for all species/shelterwood stage/growing season combinations.

first removal and final cuts differed in RM seven times and these were in the third or fourth growing season for each species.

RM did not differ among growing season for any species in the uncut and preparatory cut treatments (Table 4). Conversely, all species had their smallest and largest RM in the first and fourth growing season, respectively, in the first removal and final cuts. RM in the second and third growing season for these two shelterwood stages was either the same as it was in the first growing season or intermediate.

At the end of the fourth growing season, there were no differences in RM among species in the uncut stands (Table 4). However, in the preparatory and first removal cuts, chestnut and northern red oak had larger RM than the other two species. Northern red and black oak had the largest RM in the final cut stands followed by chestnut and white oak.

4. Discussion

The results of this study, although preliminary, partially support the five specific research hypotheses at this time.

Hypothesis 1. The shelterwood stages will have distinct and unchanging understory light levels is partially supported. At the beginning of the study, there were four different light regimes in the four shelterwood stages; uncut (4%), preparatory cut (15%), first removal cut (48%), and final cut (89%). The three largest of these endured unchanged through the fourth growing season. However, the anthracnose outbreak raised the 4% sun in the uncut stands to that of the preparatory cut stands for the second and third growing seasons. Once the outbreak ended, the understory light regime in the uncut stands returned to the previous level. Also, the light levels in the first removal and final cuts are showing some evidence of drastically changing in the near future as the residual canopies expand and the abundant regeneration becomes taller.

The light level in the uncut treatment was slightly higher than reported in other studies (Hutchison and Matt, 1977; Floyd et al., 1978; Lorimer et al., 1994; Miller et al., 2004). This likely is due to broadcast spraying that removed some of the low understory vegetation of the sites before the study began. McCarthy and Robison (2003) reported a mean light regime of 6.6% for mature, fully stocked oak stands in southern Ohio that lacked a dense understory layer. Apparently, an average of 5% full sun is probably representative of oak stands that naturally lack this vegetative strata.

Hypothesis 2. No root development for any oak species in the uncut treatment—is fully supported by the results. In general, root development in this treatment was the same from the first to the fourth growing season for all four oak species. They did not develop more roots beyond what they grew from cotyledonary reserves during the first growing season. This finding is compatible with other oak seedling growth studies conducted in the Appalachian Mountains (Loftis, 1990a,b; Miller et al., 2004).

Hypothesis 3. The root development relationship among shelterwood stages will be uncut < preparatory cut < first removal cut = final cut for all oak species – is partially supported by the results. Root growth for black, chestnut, and white oaks in the preparatory cut was basically the same as that in the uncut treatment during the 4 years of the study. This may be due to the anthracnose outbreak making these two treatments indistinguishable in terms of understory light during the second and third growing seasons or that this light regime is incompatible with the silvics of these species or that more time is needed for root development to occur. The lack of root development for these three oak species is similar to the findings of Kass and Boyette (1998) from a study done in the Piedmont region of North Carolina. Together, both suggest that light partial cutting of oak stands provides little benefit to the regeneration of these oak species.

Northern red oak seedlings did show slight development in all aspects of root size in the preparatory cut treatment, but that trend was not clearly evident until the fourth year. This is in keeping with findings by Loftis (1990a,b) and Miller et al. (2004) that showed small, but consistent, growth for this species when dense understory shade is removed and the seedlings develop in diffuse overstory shade. In fact, this response is the basis for the herbicide-shelterwood prescription used in northern red oak–yellow-poplar stands in the southern Appalachian Mountains.

The first removal cuts created stands with large canopy gaps and average basal areas and understory light levels of 18 m^2/ha and 48%, respectively; comparable levels to other studies (Schlesinger et al., 1993; Lorimer et al., 1994; Dey and Parker, 1996). All species increased root development in this shelterwood stage by the second or third year. By the end of the fourth growing season, all aspects of root growth for all species in the first removal cuts were several-fold greater than those in the uncut and preparatory cuts.

It was expected that the root growth of all oak species in the final cut treatment would not differ from that found in the first removal cut, despite a doubling of understory light, because oaks maximize photosynthesis at about 30% of full sunlight (Bourdeau, 1954; Phares, 1971). However, only chestnut oak showed the expected non-response. White oak showed mixed results, i.e., increased RCD and RM, and all aspects of root development of black and northern red oak were significantly greater in the final cut than the first removal cut. The difference in root development for these two species between these two treatments was striking by the fourth year. In fact, excavating the black and northern red oak seedlings was difficult because their roots had grown so large.

This discrepancy between the literature and results of this study may be due differences in methodology and duration. The earlier studies were done under tightly controlled conditions, i.e., artificial light or shade cloth, seedlings grown in boxes or pots, and for a few months. They may not adequately represent actual forest conditions. This study was conducted in forests over four growing seasons. Therefore, it is reasonable to conclude for black and northern red oak that maximum root development occurs at higher light levels higher than 30% full sun.

Hypothesis 4. Differences in relative root sizes among species will reflect differences in relative growth rates by the end of the fourth growing season, is fully supported. In the three cut treatments, northern red oak, the fastest growing oak, had the largest roots while white oak, the slowest growing oak, had the smallest. Black and chestnut oak were intermediate in growth rate and root size.

Hypothesis 5. Among shelterwood stages, the RCD threshold of 6.4 mm was expected to be met or surpassed in all but the uncut treatment by the end of the fourth growing season.

After 4 years, this hypothesis is only partially supported. Northern red oak met this criterion in the first removal cut and final cut by the end of the second growing season. Chestnut oak did likewise in these treatments by the end of the third growing season. Black and white oak passed the 6.4 mm mark only in the final cut in the third and fourth growing seasons, respectively. None of the species had a RCD larger than 6.4 mm in the preparatory cut although northern red oak was close and would probably be there in a year or two. Again, the preparatory cut appears to provide little benefit to black, chestnut, and white oak seedlings.

5. Management implications

Forest managers are increasingly interested in prescribed burning oak forests, especially to control competing hardwoods during a shelterwood sequence (Yaussy, 2000; Dickinson, 2006). However, those desiring to do so are faced with two operational questions: how heavy or light should a shelterwood cut be to optimize oak root development, and how much time should pass between the cut and the prescribed fire? Findings of this study help answer these questions.

Survivorship increases for oak roots once they achieve a minimum RCD of 6.4 mm (Brose and Van Lear, 2004). Therefore, the preceding shelterwood cut must create the understory light regime conducive for development of this size RCD. Based on this study, only harvests that reduce the canopy to 50% cover or less will likely produce oak roots with the required RCD. Preparatory cuts and first removal cuts that leave more than 50% canopy cover are unnecessary if prescribed burning is anticipated and appear detrimental to regenerating oak with the shelterwood-burn technique because they inhibit root development and decrease the ability of the oak roots to withstand fire.

Once the proper shelterwood cut is made, do not rush the prescribed fire. In this study, chestnut and northern red oak seedlings growing in the first removal cuts easily reached the 6.4 mm RCD threshold within 4 years. The black and white oak seedlings were not far from that diameter and will likely attain this benchmark in a few years. Therefore, burning should occur 4–7 years after the first removal cut, depending on the predominant oak species. This time period is also important because it allows the logging slash to partially decompose so fire behavior is not too intense.

Caution needs to be exercised when applying these results outside the parameters of this study. This research was conducted on acorn-origin oak seedlings planted in fenced stands on intermediate and mesic sites on the Appalachian Plateau of Pennsylvania. Existing oak seedlings growing on other sites elsewhere may respond differently due to differences in physiological condition, site quality, interspecies competitive relationships, and deer browsing impact.

Acknowledgements

This project has involved the efforts of many people. The author is especially indebted to Wendy Andersen, Brent Carlson, Josh Hanson, Beth Irwin, Ty Ryen, and Greg Sanford for installing the study, collecting the seedlings, and conducting all the measurements. Without their help, this project could never have been done. The author also thanks the Pennsylvania Bureau of Forestry for funding the study, giving permission to use state forest land, and providing numerous types of in-kind support. John Stanovick of the USDA Forest Service, Northern Research Station graciously provided guidance on the statistical analyses. Finally, the author thanks fellow scientists at the Warren Forestry Lab for reviews of this manuscript that helped with clarity and conciseness.

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