RESPONSE OF PLANTED NORTHERN RED OAK SEEDLINGS TO REGENERATION HARVESTING, MIDSTORY REMOVAL, AND PRESCRIBED BURNING

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Abstract—Oak (*Quercus*) is difficult to naturally regenerate in many mature oak stands on productive sites in the southeastern United States, and artificial regeneration alternatives should be considered. Artificial regeneration can potentially restore or enrich the oak component at the stand level. We examined genetic and silvicultural effects on artificially regenerated northern red oak (*Quercus rubra*) seedlings three years after planting under three silvicultural prescriptions and a control. We used quality-grown seedlings from open-pollinated families to improve probabilities of success. The seedlings averaged 101 cm in height and 11.2 mm in root-collar diameter at the time of planting. Genetic differences were significant for survival and growth, but these differences may have been due to a residual nursery effect. Families with large seedlings at the time of planting were generally larger and had better survival after three years than families with smaller seedlings at the time of planting. A commercial shelterwood harvest was the only successful silvicultural treatment for artificial regeneration in this study. Trees planted in this treatment grew a total of 41 cm in height and 8.1 mm in ground-line diameter in three years. Seedlings planted in uncut stands, whether stands had been burned, treated with a midstory removal, or left untreated, had relatively poor survival (30 to 72 percent) and negligible growth (≤15 cm height, ≤2 mm ground-line diameter).

INTRODUCTION

In the southern United States, upland oak (*Quercus*) forests are an important resource, but have been declining due to regeneration failures and mortality of aging overstory trees over the last several decades (Abrams 2003, McEwan and others 2011). The loss of oak species can have drastic ecological and economic effects, particularly in southeastern forests (Oswalt and others 2009). Natural regeneration methods have been tested, but often require a series of noncommercial treatments and many years to increase the density of large oak seedlings (i.e., advanced reproduction) (Arthur and others 2012, Loftis 1990). Artificial regeneration can be used to supplement natural oak regeneration, but we currently have limited knowledge on how silvicultural treatments affect planted oak seedlings.

The idea that larger seedlings will perform better than smaller seedlings has been tested for many decades (reviewed in Dey and others 2008). However, recent developments in nursery technology to produce seedlings with relatively large aboveground and belowground systems (e.g., high-quality seedlings; Kormanik and others 2002) have gone relatively untested, particularly on productive upland sites in the southeastern United States. Furthermore, testing of genetic effects and interactions in silvicultural studies is rare. The objective of this study was to test quality-grown northern red oak (*Quercus rubra*) seedlings planted in three silvicultural treatments and a control while accounting for variation associated with genetics of seedling seed source. Results will provide managers with information on how to best use limited resources to artificially regenerate oaks on productive sites in this region.

METHODS

The study area was located in the Blue Ridge Mountain physiographic region of North Carolina on Cold Mountain Game Lands, owned and managed by the North Carolina Wildlife Resources Commission. Site characteristics were described by Keyser and others (in press). Experimental units consisted of 5-ha mature hardwood forests. Stands were similar in structure

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and averaged 32 m^2/ha in basal area in trees greater than 15 cm diameter at breast height (dbh). Treatments were implemented prior to planting and included a prescribed burn (Rx burn), a midstory removal (MR), and a commercial shelterwood harvest (SW). An untreated control was also included. All treatments were replicated three times using a completely random design. Two replications of the Rx burns were conducted in February 2009 and one was conducted in April 2010 prior to planting. Rx burns were ignited using drip torches and were set as backing fires with flanking strip head fires. The MR was conducted according to prescriptions described by Loftis (1990) in September 2008. With the exception of oak and hickory (*Carya*) species, competing midstory trees ≥5.0 cm and <25.0 cm dbh were injected with herbicide Garlon® 3A. Basal area in the control and in the Rx burn units decreased 5 percent, and basal area in the MR units decreased 15 percent. The SW basal area decreased 63 percent, leaving mostly dominant and codominant oak stems.

Northern red oak acorns were collected from six open-pollinated mother trees located in stands of the Pisgah National Forest in the Blue Ridge physiographic region in autumn 2008. Acorns were sown at a density of 65/m^2 separately by family, and the resulting seedlings were grown as 1-0 bare-root seedlings at the East Tennessee Nursery in Delano, TN, using prescriptions developed to produce high-quality seedlings (Kormanik and others 2002). Trees were lifted in March 2010 by family and visually graded to select the largest 30 percent from each seed lot (based primarily on root-collar diameter) to improve seedling quality (Clark and others 2000).

We used a randomized complete block design with single tree plots, and 14 blocks were planted in each experimental unit (84 trees). A total of 168 trees per family (1008 seedlings total) were planted using 3 by 3 m spacing. We collected survival, stem height, and ground-line diameter (GLD) data just after planting (April 2010) and for three years after planting (growing seasons 2010-2012). Data were analyzed using a general linear mixed model (LM) to determine the effects of silvicultural treatment, year since planting, and genetic family on height and GLD. A generalized linear mixed model (GLMM) was used to analyze the effects of treatments on survival (alive=1, dead=0) for each year after planting. We specified a binary response distribution with a logit link function, and GLMMs were modelled on event=1. If main effects of treatments were significant in the LMs and GLMMs, we computed comparisons using Tukey's mean separation method.

RESULTS AND DISCUSSION

Silvicultural treatment and family affected survival, height, and GLD after three growing seasons (table 1 and 2). The interactions between family and silvicultural treatment for survival were significant probably because one family (NRO11) had higher survival than other families in the SW treatment each year after planting. Families had similar survival in all other silvicultural treatments. The two-way interactions between treatment and family were not significant for height or GLD (table 2). The three-way interaction among year, treatment, and family was significant for height because some families performed better in some treatments in some years and performed similarly in some treatments in other years.

When averaged across treatments, NRO11 generally had higher survival than other families each year after planting (fig. 1). This family also exhibited relatively large height and GLD in all years, including at the time of planting (fig. 2). Families maintained similar height and GLD growth rankings over time (fig. 2). These results indicate that larger seedlings at planting will maintain size advantages over smaller seedlings and will have improved survival, which has been shown in other studies (reviewed in Dey and others 2008 and 2012). Family effects in this study, therefore, may be confounded with a nursery effect because seedling size attributes from the nursery could mask true genetic differences after planting (Pinto and others 2011). Our family seed lots were not replicated at the nursery, and

Table 1—Generalized linear mixed model for survival for the first three years after planting northern red oak

	Treatment		Family		Treatment*Family	
Year	F	P	F	P	F	P
1	69.57	<0.0001	67.05	<0.0001	139.45	<0.0001
2	94.51	<0.0001	82.33	<0.0001	130.84	<0.0001
3	78.39	<0.0001	68.61	<0.0001	112.4	<0.0001

initial size advantages exhibited by certain families could be due to nursery growing conditions for that family seed lot (e.g., distance to nearest watering riser and elevation of bed). However, the size advantages could also be related to acorn size at sowing, which is an inherited trait (Kormanik and others 1998, Korstian 1927). Genetic differences in early field performance of northern red oak in the nursery and after planting is a well-known phenomenon (Kriebel 1965), and family rankings can change over time (Schlarbaum and Bagley 1981, Kriebel and others 1988). Managers should use a genetically diverse seed mix to avoid the chance of planting only one or two families that produce small seedlings in the nursery or poor performing families in the field. Families had similar survival in the noncommercial treatments (Rx burn, MR, and control) for each year after planting, indicating genetic and/or seedling size differences could not be discerned in low light environments where growth was negligible.

Seedlings in the SW treatment had the highest survival and had the largest height and diameter after three growing seasons (fig. 3 and table 3). In fact, the SW treatment was the only treatment to have significant

Table 2—General linear mixed models with repeated measures for height and ground-line diameter (GLD) three years after planting northern red oak

		Height		GLD	
Effect	Denominator DF	F	P	F	P
Treatment	8	6.85	0.0134	11.24	0.0031
Family	818	18.78	<0.0001	9.52	<0.0001
Treatment*Family	818	1.45	0.1163	1.01	0.4371
Year	3	90.98	<0.0001	330.17	<0.0001
Year*Treatment	1893	27.09	<0.0001	126.75	<0.0001
Year*Family	1893	1.65	0.0539	1.58	0.0723
Year*Treatment*Family	1893	1.50	0.0179	0.67	0.9575

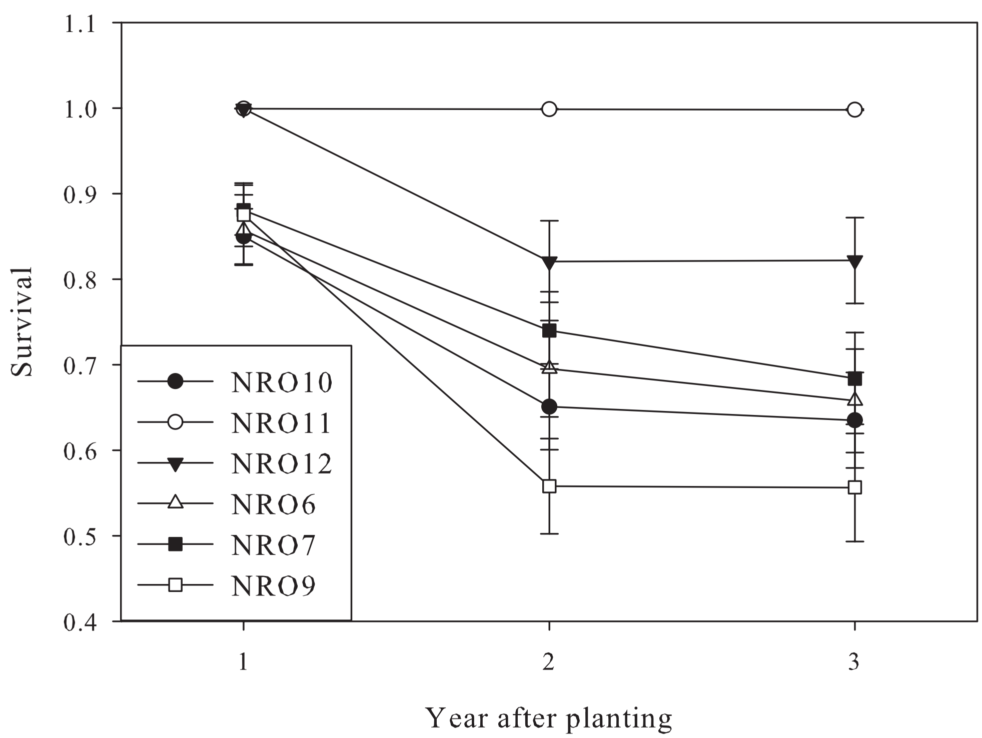

Figure 1—Survival least-squares means three years after planting six genetic families of northern red oak.

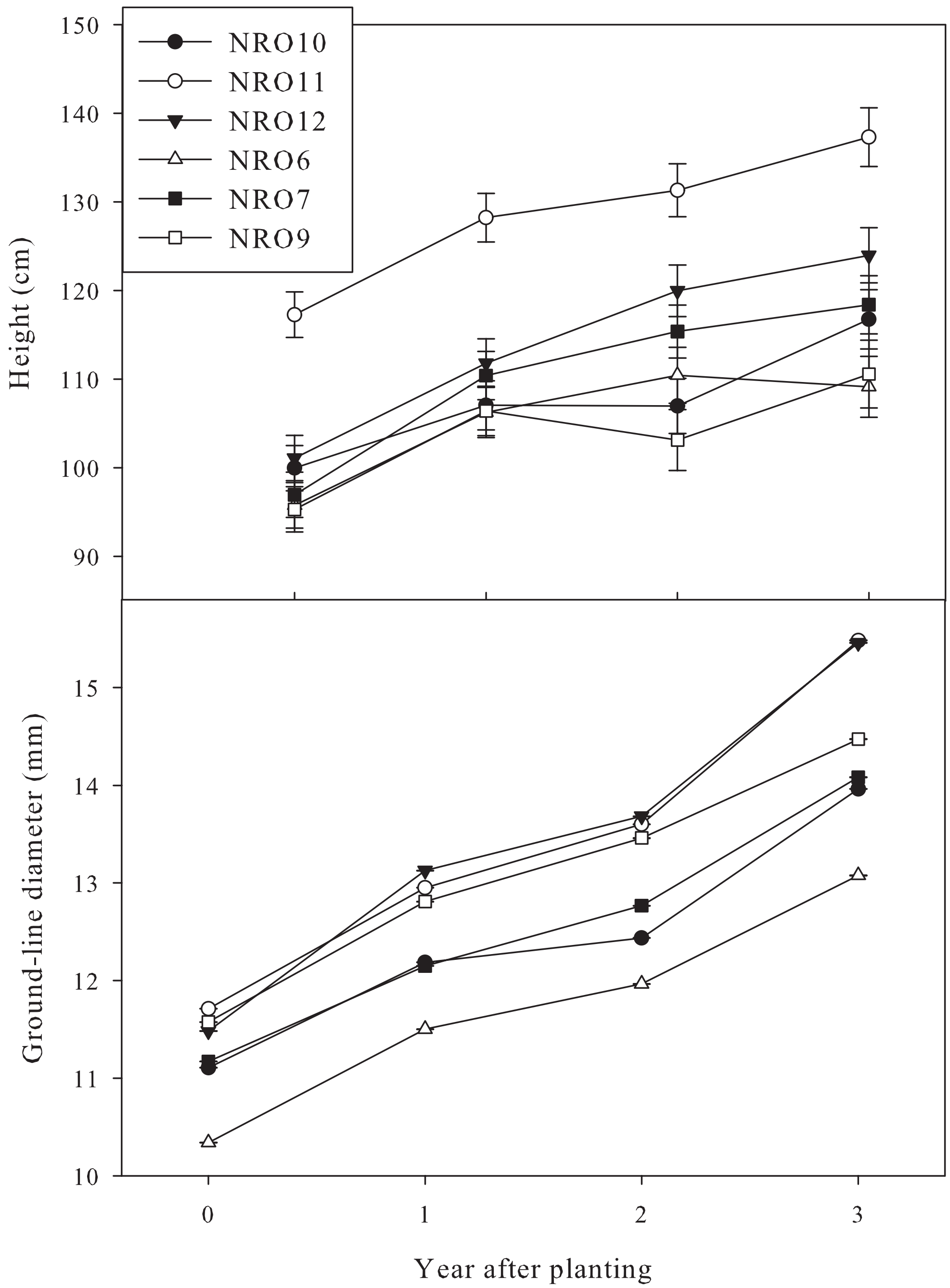

Figure 2—Height and ground-line diameter least-squares means three years after planting six genetic families of northern red oak.

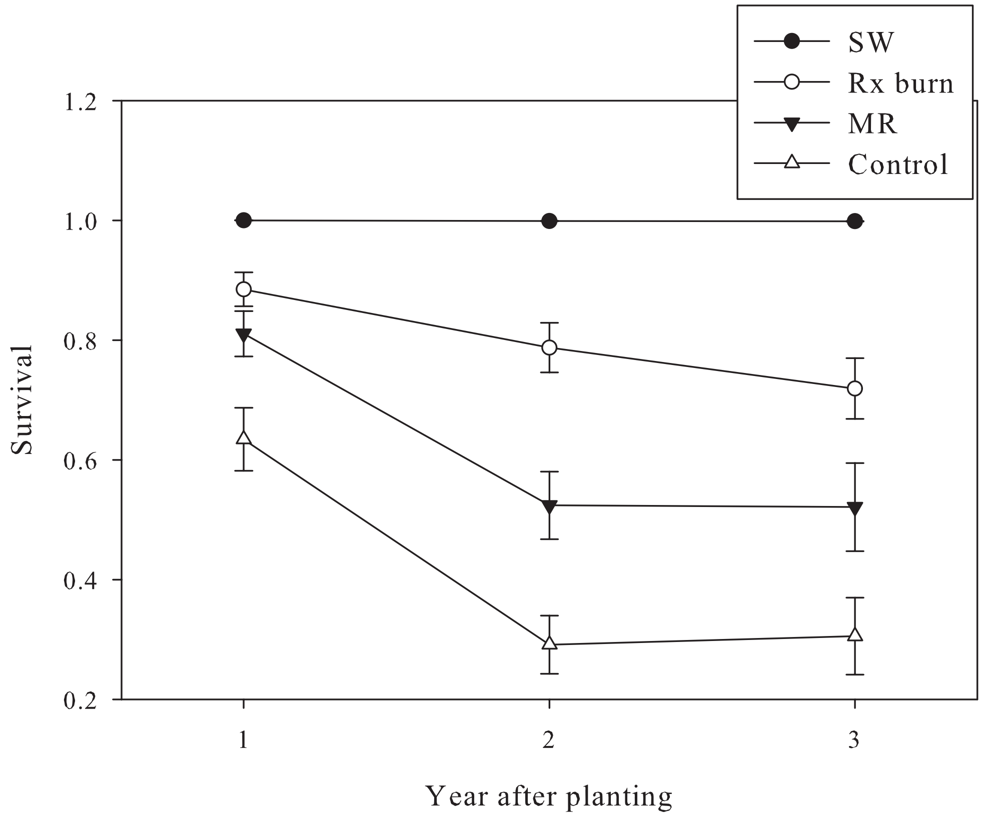

Figure 3—Survival least-squares means for three silvicultural treatments and a control three years after planting northern red oak. SW = commercial shelterwood harvest, Rx burn = prescribed burn, and MR = midstory removal.

Table 3—Height and ground-line diameter (GLD) least-square means at the time of planting and for the first three years after planting northern red oak. Means followed by the same letter are not significantly different

	Year 0		Year 1		Year 2		Year 3	
				Height (cm)				
Control	99	fgh	105	cdefg	102	defg	104	cdefg
MR	101	gh	113	bcdef	113	bcdef	113	bcdef
Rx burn	101	fgh	118	bcd	119	bc	116	bcde
SW	103	eh	112	cdfg	123	b	144	a
				GLD (mm)				
Control	11.2	gjkl	12.6	cdefhi	12.5	cdefhi	13.2	cdef
MR	11.4	fkl	12.1	dij	12.2	cdeghi	12.9	cegh
Rx burn	11.0	il	12.4	cdefgh	11.9	ejk	12.7	cdfgh
SW	11.2	hijk	12.7	cdefg	15.4	b	19.3	a

MR = midstory removal, Rx burn = prescribed burn and SW = commercial shelterwood harvest.

yearly height growth after the first year (table 3). Three-year survival was 99 percent in the SW stands, and trees grew an average of 41 cm and 8.1 mm in height and GLD, respectively. The improved survival and growth in the SW treatment over other treatments was expected because growth rates increase as canopy openness increases from relatively low levels (Johnson 1984, Lhotka and Loewenstein 2009, Morrissey and others 2010, Spetich and others 2002).

The Rx burn and MR treatments had statistically similar survival rates in years 1 and 3 after planting despite a 20-percent higher survival rate in the Rx burn stands. The control had the lowest survival rates, averaging 30 percent in year 3; however, this was not statistically different than the MR treatment (52 percent). The lack of statistical differences in survival among treatment means was due to high variation among replications, and indicates more replications of treatments were needed. Variation among experimental units with the same treatment could be due to differences in timing of treatments for the Rx burn units, or it could be related to site differences among replications of the same treatment (e.g., aspect, elevation, soil moisture availability, and nutrient availability). Exploratory analysis using potential explanatory variables should be conducted to elucidate explanation for the relatively high variation in survival.

Despite the low power of the study, the low survival in the MR treatment would be considered unacceptable for most commercial planting operations. We suspect that the slight increases in survival in the Rx burn treatment over the control and MR treatments could be related to nutrient increases from burning organic matter prior to planting (Blankenship and Arthur 1999). In contrast to this study, other studies have found oak seedlings had adequate survive in noncommercially treated underplantings up to seven years after planting with slight increases in light availability (Buckley and others 1998, Lhotka and Loewenstein 2009, Parrott and others 2012, Schweitzer and others 2006). However, seedlings planted in this study were larger than these previous studies, which may have reduced their ability to maintain proper root/shoot ratios under a low light environment (Struve and others 2000). Oswalt and others (2006) also found reduced survival (58 percent) in uncut stands after two years compared to harvested stands (>80 percent) for seedlings sized similarly to those in our study.

Seedlings in the noncommercial treatments had relatively poor growth rates compared to the SW treatment (table 3). The MR, the Rx burn, and the control treatments did not grow in height from year 1 to year 3, and the MR treatment was the only noncommercial treatment that had significant GLD growth during this time. The poor growth in the control was similar to previous studies that found oak seedlings did not grow under full canopy conditions (Buckley and others 1998, Parrott and others 2012). In contrast to our study, large oak seedlings (~100 cm height) grew 26 cm in height in control stands after two years in a study in western Tennessee (Oswalt and others 2006). The height growth reported by Oswalt and others (2006), however, could have been from new sprouts originating after stem dieback, and may not represent increases in total height (as we measured). The slightly improved GLD growth found in the MR treatment compared to the control treatment was expected because removal of midstory or understory competition above natural or planted seedlings improves growth, particularly of the root system (Lhotka and Loewenstein 2009, Loftis 1990, Parrott and others 2012, Paquette and others 2006). The relatively poor growth of seedlings in the Rx burn was probably due to low available light. The burns were highly variable and were of relatively low intensity overall. Additionally, midstory stems deadened by the fire produced understory sprouts within a year of the burns, which probably increased understory shade to planted seedlings.

If we use GLD as a surrogate for root growth (Grossnickle 2012), trees had more relative growth in the root system compared to stem growth in the SW and control treatments. For example, trees had a 40-percent increase in relative stem height and a 72-percent increase in relative GLD in the SW stands from the time of planting until year 3. The seedlings in the control grew 5 percent in height and 18 percent in GLD over three years. In contrast, the MR and the Rx burn treatments had GLD-relative growth rates similar to their height-relative growth rates (approximately 12 and 15 percent for the MR and Rx burn treatments, respectively). Oak seedlings rebuild root systems damaged during lifting and planting at the expense of stem growth, a process known as transplant shock (Struve and others 2000). Results suggest that at the two extremes of disturbance in this study, with the most extreme in the SW and the least extreme in the control, seedlings built root systems at the expense of aboveground biomass during the early years when undergoing planting shock. Seedlings planted under the intermediate disturbance regimes of the MR and Rx burn treatments recovered their root systems while simultaneously building aboveground biomass in similar proportions. Unfortunately, information comparing growth of oak seedlings planted under a gradient of disturbance regimes is limited. Kolb and Steiner (1990) found direct-seeded northern red oak had relatively balanced root/shoot ratios when grown with an intermediate light intensity and relatively high root/shoot ratios when grown in full sun.

MANAGEMENT IMPLICATIONS

We propose that the MR and control treatments as applied in this study are not viable treatments for artificial regeneration of northern red oak due to low survival and growth rates after the first three growing seasons. The Rx burn was marginally successful in terms of survival, but growth was negligible. The most efficacious treatment was the SW treatment; seedlings were able to recover from transplant shock and grow significantly each year, resulting in a 14-cm gain in height and a 2.7-mm gain in GLD per growing season. We expect height and GLD growth to improve in the SW stands as trees age and root systems fully recover from transplant shock, assuming no major future stress to the trees (Struve and others 2000).

Family differences in survival and growth were significant, but genetic differences may have been confounded with a nursery effect. Regardless, results indicate managers should use a genetically diverse seed mix from locally adapted sources to avoid the possibility of planting only poor-performing families.

A portion of the SW and the Rx burn treatments were recently burned again as part of management prescriptions for this study. Recovery from burning will be important to follow because managers are increasingly using fire to improve oak regeneration (Arthur and others 2012). Predictions that survival and growth after burning will depend on seedling size at planting are currently being tested.

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