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Article

Effects of Visual Grading on Northern Red Oak (*Quercus rubra* L.) Seedlings Planted in Two Shelterwood Stands on the Cumberland Plateau of Tennessee, USA

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Abstract: Artificial regeneration of oak has been generally unsuccessful in maintaining the oak component in productive upland forests of eastern North America. We tested visual grading effects on quality-grown northern red oak (*Quercus rubra*) seedlings planted in two submesic stands on the Cumberland Plateau escarpment of Tennessee, USA. Seedlings were grown for one year using advanced fertilization and irrigation protocols to increase overall size of seedlings, but large variability in size was still evident. Seedlings were divided into two grades prior to planting. The "standard" grade represented seedlings that had undergone a light culling, and the "premium" grade represented the highest quality seedlings. Seven years after planting in a midstory-removal stand, 50 percent of trees survived, growth was negligible, and seedling grade had no effect on survival and yearly growth. In a shelterwood harvest stand, premium grade seedlings had taller height and larger basal diameter (BD) (241 cm and 29.5 mm, respectively) compared to standard seedlings (201 cm and 25.9 mm, respectively), and a two-year height growth advantage was achieved by planting premium grade compared to standard grade seedlings. Competitive ability and planting shock were similar between grades, and we postulate that an exceptional drought and large size variability in both grades equalized response. While our findings should be confirmed through additional testing, they suggest currently accepted seedling quality standards for northern red oak should be refined to improve regeneration efforts on productive sites in the eastern United States.

Keywords: artificial regeneration; competitive ability; dominance; midstory removal; planting shock; seedling quality; shelterwood harvest; stem dieback

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1. Introduction

Changes in disturbance regimes and increases in precipitation in the 20th century have led to a widespread oak (*Quercus*) regeneration problem across much of eastern North America [1–3]. Oak regeneration is typically present in stands where oak is the dominant genera of the overstory, but is often too small to be competitive when the stand is regenerated, particularly on mesic sites [4,5]. Decline of the oak overstory will have profound consequences for ecosystem function and utilitarian values, because oak has been functioning as an ecological keystone species since the demise of the American chestnut (*Castanea dentata*) in the early 20th century [6]. Oaks are also one of the most important sources of timber and wildlife food and habitat resources in North America, particularly in the 5.3 million ha Cumberland Plateau [7,8], which is the westernmost physiographic province of the Appalachian Highland realm. In contrast to the regeneration problems in North America, northern red oak in Europe has been successfully naturalized, particularly where competing midstory species were controlled [9].

Self-replacement of oak species might be achieved through a series of non-commercial treatments (e.g., fire, herbicide) [9–12], but these practices are sometimes cost-prohibitive or logistically challenging for many landowners. For example, prescribed burning to promote advanced oak reproduction requires that small oak seedlings are present prior to disturbance, and may require multiple burns and/or a very short burn window [11,12]. The use of herbicides prior to a regeneration harvest has been used to increase size of small oak regeneration on high-quality sites of the southern Appalachian mountains and Cumberland Plateau, but resulted in oak seedlings less than 11 mm in basal diameter after seven growing seasons [13,14]. In contrast to natural regeneration methods, a 11 mm oak seedling can be reliably produced in one year in a commercial nursery, particularly if visual grading criteria are employed after lifting [15,16].

Artificial regeneration is a management option when natural regeneration is absent or when advanced reproduction is desired quickly. Oak planting studies, however, have been conducted for decades, but with few successes on upland medium to high-quality sites [site index for northern red oak (*Q. rubra*) >22 m; [17,18]]. Artificial regeneration failures are often attributed to slow growth of planted seedlings in relation to competition [19–21] and from deer browsing small seedlings [22]. The use of poor-quality seedlings (*i.e.*, small size, poor root development), the use of non-local seed source(s), and a multitude of interacting extrinsic and intrinsic factors have been cited as contributing to planting failures [18,23].

A major deterrent to growth of oaks in the first year or two after planting has been planting shock, a period of negligible above-ground growth while the tree recovers from root system damage endured during nursery lifting and field planting operations that sometimes causes mortality [24]. Planting shock can be more pronounced in taller bare-root oak seedlings [25–27], but studies conflict on whether the advantages of planting taller trees will eventually be negated by increased incidence of planting shock [27]. Inferences on relationships between planting shock and seedling size are limited because most studies have used relatively small trees [28]. Identification of seedling characteristics, nursery, and genetic stocks that decrease planting shock would be an important step in improving efficiency of artificial regeneration efforts.

Planting prescriptions for upland hardwood sites, including site preparation treatments, seedling quality standards, and post-planting maintenance, have been largely based on studies conducted in stands with poor to medium productivity (e.g., site index for northern red oak (*Q. rubra*) ≤22 m) in the Ozark or Boston Mountain region [19,29,30]. Technological, logistical, and seed source limitations, as well as a general lack of industrial support for hardwood planting research have posed barriers to refinement of planting prescriptions on productive sites where competition is intense. Prescriptions are not yet refined for productive sites in eastern hardwood forests, where planted trees need to be competitive with fast-growing yellow-polar (*Liriodendron tulipifera* L.) and the ever-increasing competition from maple (*Acer* L.) [31]. Furthermore, artificial regeneration studies using quality-improved seedlings are rare on sites treated with non-commercial methods designed to improve the natural oak component (e.g., prescribed fire, herbicide midstory removal) [32–35].

Advanced irrigation and fertilization nursery protocols have been developed for some time to improve seedling quality [15,16,31], but empirical tests of these protocols are relatively few and/or short-term [33–35]. Even with advanced nursery protocols, variability in the seed bed is still large resulting in seedlings exhibiting a range of sizes [15,16]. Seedling uniformity is important for reliable predictions of performance and for logistical concerns. For example, it is easier to estimate resources needed for seedling transport if they are relatively the same size; it is more efficient to use a single type of planting tool to plant trees of similar size. Visual grading of seedlings may be an important component of planting prescriptions on productive sites to improve seedling uniformity, overall quality, and to reduce associated resources needed to plant trees. Seedling grading criteria for hardwood seedlings, however, remains largely unrefined and untested for productive sites in the eastern United States.

We conducted a study to quantify differences in two seedling grades of northern red produced from a visual grading process, and to test differences in seedling performance between these two seedling grades. While visual grading has been repeatedly tested for relatively small northern red oak seedlings planted on moderate to poor quality sites [18,23], we used seedlings grown using advanced nursery protocols and planted on productive sites (site index for northern red oak ≥22 m) where vegetation competition is intense. We specifically tested survival, growth, and competitive ability of 1–0 northern red oak seedlings planted in a regeneration harvest and planted in a non-commercial midstory-removal treatment (*cf.* [13]). We tested a "standard" seedling grade by lightly culling seedlings, similar to methods currently being conducted by commercial hardwood nurseries in the southern USA that utilize nursery protocols to produce high-quality seedlings [16]. We also tested a "premium" grade that results from a stringent culling of seedlings, a practice that is not yet conducted as part of most commercial nursery programs. We proposed the following research hypotheses:

1. Visual grading would result in two distinct size classes that differed in height, root-collar diameter (RCD), and number of roots, when compared to the overall nursery population;
2. The larger seedling grade will exhibit the highest survival, greatest growth, and have the best competitive ability seven-years after planting in a regeneration harvest;
3. Seedling grade will have minimal effects on growth or survival in the mid-story removal stand;
4. Planting shock, identified by stem dieback and mortality, will be more pronounced for the larger seedling grade and in the first year after out-planting.

2. Methods

2.1. Study Areas

Our study was conducted on the Cumberland Mountains section within the Cumberland Plateau physiographic province [36]. Much of the land was historically disturbed through logging, fire, conversion to agriculture or pine plantations, grazing and natural phenomenon [37], resulting in a landscape dominated by disturbance-dependent species, primarily oak [38,39].

Our study sites were located within the North Cumberland Wildlife Management Area, Royal Blue and Sundquist Units in Campbell County, Tennessee, and were managed by the Tennessee Wildlife Resources Agency (TWRA). The area is characterized as the Wartburg Basin and Jellico Mountain Landtype Association within the Thrust Block Interior of the Cumberland Mountain Region [36]. Site index for upland oaks averaged 25 m (base age 50). Soils are well drained, formed in loamy colluvium with acid siltstone, shale and sandstone.

2.1.1. Midstory-Removal Stand

The stand was approximately 8.1 ha in size, on a northeast facing slope and averaged 609 m in elevation. Basal area prior to midstory removal was approximately 25 m^2/ha for trees ≥14 cm diameter at breast height (dbh). Primary overstory species composition was northern red oak, yellow-poplar, white ash (*Fraxinus americana* L.), chestnut oak (*Quercus prinus* L.), and white oak (*Q. alba* L.). The understory was primarily composed of red maple (*Acer rubrum* L.), yellow-poplar, sourwood (*Oxydendrum arboretum* (L.) DC.), and northern red oak, but most of the natural oak regeneration was not in a competitive position (e.g., <50 cm in height). The mid-story removal was conducted in August 2007, approximately 5 months after the trees were planted, using a non-commercial tree injection treatment. We mixed 23 percent Garlon® 3A, 4 percent Arsenal® in water with an oil carrier and injected 1 mL of solution per 5 cm dbh to undesirable species (e.g., red maple, sassafras (*Sassafras albidum* (Nutt.) Nees), yellow-poplar). Trees ≥3 cm in intermediate or suppressed canopy positions were treated, excluding oak and hickory (*Carya* Nutt.). The treatment resulted in a 25 percent basal area reduction that is intended to increase diffused light to the forest floor and increase the size of existing oak regeneration [13].

2.1.2. Shelterwood Harvest

The study area was approximately 6.1 ha in size, on a north-facing slope and averaged 472 m in elevation. Basal area prior to harvest for trees ≥14 cm dbh was 19.5 m^2/ha. Overstory species composition was primarily white oak (*Quercus alba* L.), northern red oak, yellow-poplar, pignut (*Carya glabra* Mill. Sweet) and mockernut hickory (*Carya tomentosa* Poir. Nutt.), sourwood, and red maple. Most of the natural oak regeneration was not in a competitive position (e.g., <50 cm in height) prior to harvest. The stand was harvested in autumn 2006, approximately 4 months prior to planting, using a two-aged regeneration method to leave approximately 13 m^2/ha of basal area in overstory trees (≥14 cm dbh). The resulting stand is two-aged because the harvest leaves an age class in the residual overstory trees and an age class in the regenerating trees. The regeneration treatment objectives were to favor oak and hickory species for hard-mast production for wildlife, to increase structural diversity of the stand, and to improve forest health conditions by removing diseased or dying trees.

As part of the TWRA's management protocols for planted seedlings, an herbicide release was conducted to release seedlings from overtopping competition in June 2010. A 25 percent mixture of Garlon 4® was applied with an oil carrier using a full basal spray to all non-preferred trees (all arborescent vegetation except oaks, hickories (*Carya*), and cherry (*Prunus* L.)) <14 cm dbh that were directly overtopping a planted seedling.

2.2. Experimental Material and Treatment Design

In the fall of 2005, we collected acorns from a single northern red oak mother tree in the Watauga Seed Orchard, Cherokee National Forest in Carter County, TN, USA. The orchard has been rogued three times to remove families that had poor acorn production, poor growth of progeny, or to accommodate spacing considerations [31]. The mother tree's original seed source was Morgan County, TN, USA, within the Cumberland Plateau province. The resulting progeny from the mother tree were putative half siblings, a product of open-pollination from a known female parent and unknown male parents. A single open-pollinated family was used to minimize the effects of genetic variation and genotype–environmental interaction in the experiment. This mother tree was selected because it was locally adapted to the planting sites and it produced acorns in sufficient numbers for this study. Progeny from this mother tree has been planted in numerous other progeny tests and silvicultural tests across multiple locations, and has not exhibited any peculiarities in its progeny. Acorns were subjected to the float/sink test prior to sowing [40]. Approximately 4000 acorns were hand sown at the Georgia Forestry Commission's Flint River nursery near Byronville, GA in prepared soil beds at a spacing of 65 per·m^2. The seedlings were fertilized according to prescriptions to produce high-quality seedlings [16] and irrigated as needed for one growing season. The resulting seedlings had good germination (85 percent) and growth representative of average northern red oak planting stock produced from the Flint River Nursery.

Approximately 3400 seedlings were lifted on 26 February 2007, during which they were undercut at 25 cm, a standard height for undercutting for hardwood seedlings [15]. From the pool of 3400 seedlings, we first randomly selected approximately 180 as a representative sample to assess seedling size of the family population. From the remaining seed lot, we randomly selected 300 "standard" grade seedlings. based primarily on phenotypic characteristics and primarily size of root-collar diameter (RCD), but other characteristics were also considered such as damage or disease, stem height, tap root size, bud set, and number of first-order lateral roots (FOLR) [15]. Standard seedlings represented 85–90 percent of seedlings in the nursery bed, and the remaining 10–15 percent of trees were considered cull trees (*i.e.*, trees of insufficient quality to be sold commercially). Standard seedlings represented what was currently being sold by commercial hardwood nurseries that utilize prescriptions to grow high-quality nursery stock (*cf.* [16]). To mimic the nursery's grading practices, standard grade seedlings represented a wide range of sizes, with some trees as large in height and RCD as the premium grade seedlings. We then randomly selected 300 "premium" grade seedlings using the same phenotypic characteristics described above, but premium grade seedlings represented the largest 40–50 percent of seedlings in the seed lot, and were theorized to be the most competitive after planting [15,33,34]. The seedlings were planted on a 3.7 by 3.7 m spacing (748 trees per ha) using JIM GEM® KBC planting bars modified to be 30 cm in width. A total of 292 seedlings were planted at the shelterwood harvest and 300 seedlings were planted at the midstory removal from 15–19 March 2007. The planting design at each site was a pseudo, completely random design where the two seedling grades were planted at alternating planting spots.

2.3. Data Collection

Seedlings were measured for height, RCD, and number of FOLR just after lifting. A FOLR was defined as a root stemming from the main tap-root that was at least 1 mm at the proximal end. The root collar was defined as the transition zone between the above and below-ground portion of the tree and is demarcated by a color change in the stem. The stem height was measured from the root collar to the top of the tallest live bud.

We measured seedlings for stem height and basal diameter (BD) just after planting, and in late August/early September after the terminal bud had set, but before leaf abscission in the 2007, 2008, 2009, 2011, and 2013 growing seasons. We measured height and BD during the dormant season (November through February) during growing seasons 2010 and 2012. Seedlings had set bud by late August; therefore, we assumed that growth measurements taken in the late summer or in the dormant season would be similar. We measured stem height to the nearest 1 cm from the ground to the tallest live bud using a standard height pole. We measured BD where the stem emerged from the litter layer using a digital or dial caliper to the nearest 0.1 mm. Dieback to the main stem was identified as mortality of the top portion of the main stem, with live buds present below the dead portion of the stem.

In the shelterwood harvest plot, we measured the height of the tallest understory competitor within 0.00054 ha (1.3 m radius) circular plots. The plots were centered on half of the planted trees, which we randomly selected from each grade. This size plot was chosen because it approximates the amount of space a dominant or codominant tree inhabits upon crown closure, and can be used to calculate an average stocking value [41]. Understory trees were defined as trees ≥30 cm height but <4 cm dbh. The competition plots were measured at the same time seedling measurements were conducted in 2007, 2008, 2009, 2011, and 2013. Competition data were not collected in 2010 or 2012.

At the same time, competition measurements were taken, we assessed if the tree was free-to-grow in the understory and midstory canopy layers. Midstory trees were defined as trees between 4 and 13.9 cm dbh. A tree was determined to be free-to-grow if the terminal bud of the planted seedlings was not directly overtopped by stems or leaves from competing trees in the respective canopy layer. The location of the competing trees when determining free-to-grow status could be outside or inside the

0.00054 ha competition plot. Midstory free-to-grow status was only collected in 2009, 2011, and 2013 because midstory was nearly absent prior to 2009.

2.4. Data Analysis

In the shelterwood harvest stand, planted seedlings were coded as dominant in the understory if their height was at least 80 percent of the height of the tallest understory competitor within the competition plot [19,42]. If the seedling was shorter than 80 percent of the height of the tallest competitor, the tree was coded as not dominant. We did not include dead seedlings in calculations for dominance because we were interested in evaluating survival separately from dominance.

All data were analyzed using SAS (version 8.12; SAS Institute, Cary, NC, USA) [43] and an error level of 0.05 was used to indicate statistical significance for all analyses. We calculated Pearson correlation coefficients among nursery seedling characteristics for each seedling grade and for the random nursery sample. We determined differences in height, RCD, and number of FOLR among the two seedling grades and the random nursery sample using an analysis of variance (PROC GLM). If main effects were significant, we computed least-squares means comparisons using the PDIFF option.

Analyses of seedling performance were conducted for each site separately. We analyzed height and BD data using general linear mixed models (LMM) with PROC MIXED. Nursery seedling grade and year since planting were fixed effects in the height and BD models. We used PROC GLIMMIX in SAS to conduct generalized linear mixed modelling (GLM) on binary dependent variables survival (alive = 1 or dead = 0) and stem dieback to the main leader (presence = 1 or absence = 0) for both the midstory removal and the shelterwood harvest site. At the shelterwood harvest site, we also used GLMs to test seedling grade and year since planting effects on understory dominance of live trees (dominant = 1 or not dominant = 0), and free-to-grow status in the understory and midstory (free-to-grow = 1 or not free-to-grow = 0). We selected GLMs over LMMs for binary response data to accommodate for violation of non-normality assumptions [44,45]. We specified a binary response distribution with a logit link function, and GLMs were modelled on event = 1. We determined fit of all GLMs to be adequate because the confidence intervals of the fixed effect estimates were not exceedingly large (e.g., <6 times the standard error of the estimate) [44]. Overdispersion of the residuals was checked using a Pearson chi-square test, and all models had values approximating 1, indicating a lack of overdispersion. Year since planting was used as a repeated measure variable with an autoregressive covariance structure in LMMs for height and BD and in GLMs for stem dieback, understory dominance, and free-to-grow status in the understory [46]. The GLMs were conducted separately by year for free-to-grow status in the midstory due to lack of convergence when year was included as a repeated measure. We conducted GLMs for survival separately for each year because survival is not appropriate as a repeated measures variable.

Normality assumptions of LMMs were tested using the Shapiro-Wilk test for normality and by examining plots of residuals. The probability test for significance in the Shapiro-Wilk test is highly sensitive; therefore, we identified normality problems only when the W-statistic was <0.9. All of the linear mixed models met assumptions for normality of residuals. Homogeneity of variance assumptions were tested for each model by examining residuals *versus* predicted values. Unequal variance was added if a likelihood ratio test indicated the unequal variance model was justified, and degrees of freedom were accordingly adjusted using the Kenward-Roger method. When main effects or interactions in models were significant, we computed comparisons among the least-squares means using the PDIFF option, and we used macros [47] to compare treatment means.

3. Results

3.1. Grading Effects on Seedling Quality

Visual grading of nursery seedlings resulted in two distinct grades, and both were significantly larger in height (df = 774, F = 115.7, $p < 0.0001$), RCD (df = 774, F = 161.5, $p < 0.0001$), and had more FOLR (df = 774, F = 18.4, $p < 0.0001$), when compared to the random nursery sample (Table 1). The premium grade seedlings represented a 54, 35, and 26 percent increase in mean height, RCD, and number of FOLR, respectively, compared to means for the random sample; similarly, standard seedlings represented a 28, 13, and 18 percent increase. The premium seedlings represented a 20 percent increase in mean height and RCD, and a 7 percent increase in mean FOLR over the means for standard seedlings. The random sample did not contain seedlings as tall in height or as large in RCD as seedlings in the premium or standard grades. For example, the premium grade had 19 seedlings and the standard grade had six seedlings larger in RCD, respectively, than the largest seedlings (13.7 mm) in the random sample. Both the premium and standard grades had relatively similar ranges in RCD and FOLR, but the shortest seedling in the premium grade was 17 cm taller than the smallest seedling in the standard grade.

Table 1. Least-squares means, followed by standard errors, and ranges of stem height, root-collar diameter (RCD), and number of first-order lateral roots (FOLR) for two seedling grades and a random sample of 1–0 bare-root northern red oak nursery seedlings. Means followed by the same letter are not significantly different.

	Height (cm)		**RCD (mm)**		**No. of FOLR**	
	Mean	**Range**	**Mean**	**Range**	**Mean**	**Range**
Premium	121 (2) a	42–176	11.5 (0.1) a	5.8–16.7	16 (0.3) a	4–30
Standard	101 (2) b	25–167	9.6 (0.1) b	5.8–17.6	15 (0.3) b	4–29
Sample	79 (2) c	15–162	8.5 (0.1) c	3.2–13.7	12 (0.5) c	1–30

RCD was most strongly correlated with other variables within the random sample population and the two seedling grades (Table 2). The height-FOLR number correlation within the premium grade was not significant. Correlations between seedling variables were lower within each seedling grade compared to the random sample, and were lowest within the premium grade.

Table 2. Correlation values, with associated *p*-values, among height, root-collar diameter (RCD), and number of first-order lateral roots (FOLR) for two seedling grades and a random sample of 1–0 bare-root northern red oak nursery seedlings.

	Premium	Standard	Sample
Height-RCD	0.28 (<0.0001)	0.55 (<0.0001)	0.83 (<0.0001)
RCD-FOLR	0.32 (<0.0001)	0.59 (<0.0001)	0.77 (<0.0001)
Height-FOLR	0.05 (0.4223)	0.39 (<0.0001)	0.62 (<0.0001)

3.2. Seedling Grade Effects on Survival, Growth, and Competitive Ability

3.2.1. Midstory-Removal Stand

Seedling grade did not affect survival in any year in the midstory removal stand (df = 304, F = 0.84, $p = 0.3590$). The highest mortality occurred the first year, when 32 percent of trees died (Figure 1). Survival slightly decreased each year thereafter, averaging 48 percent by year 7. Interactions between seedling grade and year were not significant for height or BD, but main effect of seedling grade on height and BD was significant (Table 3). Premium grade trees were 7 cm taller and 1.1 mm larger in BD than standard seedlings across all years. In year 7, premium and standard seedlings had similar heights (102 cm), but premium grade seedlings were 1.3 mm larger in BD than standard seedlings (Table 4). Premium grade trees lost 16 cm in height over seven years, while standard trees had no changes in height. The tallest tree in year 7 was a standard seedling (186 cm), and a premium grade tree had the largest BD (23.2 mm). Seedling grade had no effect on stem dieback, but the *p*-value was approaching significance (Table 3). Dieback was most common in the fourth year after planting, and averaged approximately 24 percent in the first two years after planting (Figure 2). Dieback was lowest in years 3, 5, and 7.

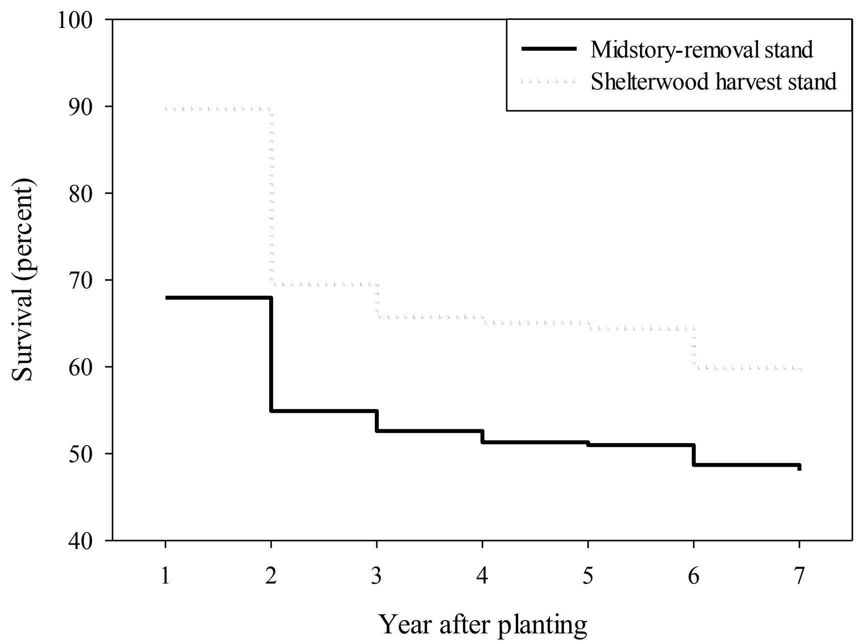

Figure 1. Survival of northern red oak seedlings in the midstory-removal and shelterwood harvest stands.

Table 3. General linear mixed models (height, basal diameter (BD)) or generalized linear mixed model (stem dieback, understory dominance, free-to-grow (FTG)) results at the midstory removal and shelterwood harvest stands where northern red oak was planted. GLMs were conducted separately by year for free-to-grow status in the midstory due to lack of convergence when year was included as a repeated measure.

	Seedling Grade			**Year Since Planting**			**Interaction**		
	DDF	F	*p*	DDF	F	P	DDF	F	*p*
Midstory removal									
Height [a]	317	5.0	0.0267	1085	6.9	<0.0001	1085	1.8	0.0937
BD [a]	359	22.6	<0.0001	931	28.5	<0.0001	931	0.3	0.9638
Stem dieback	212	3.2	0.0738	920	20.6	<0.0001	920	0.8	0.6079
Shelterwood Harvest									
Height [a]	264	18.5	<0.0001	917	74.3	<0.0001	917	1.3	0.2403
BD [a]	329	12.6	0.0004	852	197.7	<0.0001	852	0.7	0.6671
Stem dieback	235	0.1	0.7794	1078	10.4	<0.0001	1078	1.1	0.3808
Understory dominance	230	2.7	0.1043	348	13.5	<0.0001	348	0.7	0.6225
FTG in understory	235	0.0	0.9998	716	9.1	<0.0001	716	1.0	0.4283
FTG in midstory, year 3	183	0.6	0.4554	--	--	--	--	--	--
FTG in midstory, year 5	182	0.0	0.8743	--	--	--	--	--	--
FTG in midstory, year 7	172	0.1	0.2493	--	--	--	--	--	--

[a] Denominator degrees of freedom (DDF) were adjusted using the Kenward-Roger method because unequal variance was added to the model.

Table 4. Least-squares means, standard errors, and ranges in total height and basal diameter (BD) for each grade in a shelterwood harvest and in a midstory-removal stand. Means followed by the same letter within each stand are not significantly different.

	Premium				**Standard**			
Year Since Planting	**Mean**	**Std. error**		**Range**	**Mean**	**Std. error**		**Range**
Midstory removal								
Height (cm)								
0	118	2.7	a	57–182	102	2.2	e	40–152
1	113	2.9	b	11–166	101	2.4	e	10–142
2	112	3.2	bc	43–157	103	2.6	de	30–144
3	111	3.4	abd	35–166	103	2.7	de	35–155
4	100	3.5	ef	13–162	95	2.9	f	23–165
5	105	3.6	ce	19–168	102	2.9	e	29–172
6	104	3.7	cdef	18–181	100	3.0	ef	28–187
7	102	3.7	ef	21–173	102	3.1	de	33–186
BD (mm)								
0	11.0	0.20	e	7.1–18.2	9.9	0.20	fg	6.0–18.0
1	10.8	0.21	de	1.9–19.4	9.8	0.21	fg	1.9–16.9
2	9.7	0.14	g	7.7–12.3	8.6	0.14	h	5.9–12.2
3	10.4	0.25	ef	7.5–17.5	9.4	0.25	g	6.1–21.0
4	10.8	0.26	d	2.1–17.7	9.7	0.26	fg	3.6–16.0
5	11.0	0.26	d	3.0–17.5	9.9	0.26	fg	3.6–14.6

Table 4. *Cont.*

	Premium				Standard			
Year Since Planting	**Mean**	**Std. error**		**Range**	**Mean**	**Std. error**		**Range**
				BD (mm)				
6	12.9	0.27	b	2.8–20.4	11.8	0.27	c	4.3–18.0
7	13.4	0.27	a	2.9–23.2	12.1	0.27	c	7.3–19.1
				Shelterwood Harvest				
				Height (cm)				
0	123	3.1	f	45–168	100	3.1	gh	46–180
1	119	3.3	f	5–174	100	3.3	h	4–174
2	124	3.5	f	20–172	104	3.4	gh	12–179
3	126	3.7	f	14–233	108	3.6	g	21–237
4	147	3.8	e	17–298	126	3.7	f	20–281
5	187	10.2	cd	7–397	159	9.8	e	7–419
6	211	10.3	b	11–451	181	9.9	d	18–473
7	241	10.3	a	17–526	201	9.9	bc	16–495
				BD (mm)				
0	11.1	0.32	hi	6.8–19.3	9.8	0.32	jk	5.5–16.2
1	11.6	0.34	h	1.9–19.1	10.3	0.34	i	2.5–17.8
2	10.7	0.36	ij	2.3–17.4	9.5	0.35	k	2.0–15.2
3	15.0	0.37	f	2.5–27.6	13.6	0.37	g	4.2–25.4
4	17.7	0.38	e	4.0–37.1	16.0	0.38	f	4.2–32.2
5	22.4	0.99	cd	5.1–47.4	19.7	0.95	d	3.9–45.8
6	25.7	1.00	b	5.4–54.0	22.2	0.96	c	3.6–48.3
7	29.5	1.00	a	7.6–63.7	25.9	0.96	b	7.8–54.2

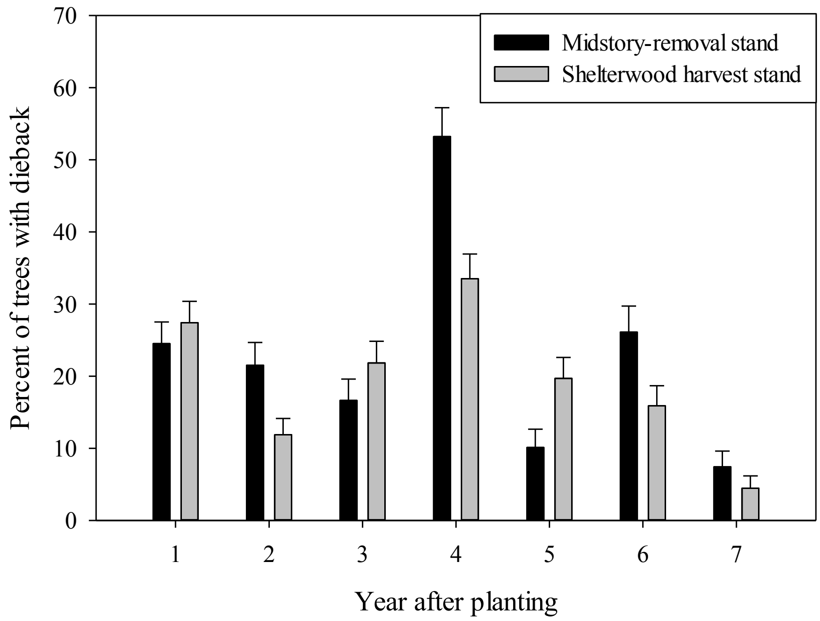

Figure 2. Least-squares means and associated standard errors for percent of trees with stem dieback of northern red oak seedlings planted in a midstory-removal and a shelterwood harvest stand.

3.2.2. Shelterwood Harvest

Seedling grade had no effect on survival in the shelterwood harvest stand in any year after planting, but the *p*-value for year 2 was approaching significance (df = 290, F = 3.32, $p = 0.0693$). Survival was relatively high (90 percent) after the first growing season, decreased 20 percent from year 1–2, and averaged 60 percent in the sixth and seventh growing seasons (Figure 1). Interactions between seedling grade and year were not significant for height or BD, but main effects were significant (Table 3). Seedlings from both grades did not grow significantly in height or BD for the first three years and two years, respectively (Table 4). Premium grade seedlings averaged 25 cm taller and 2.1 mm larger BD than standard seedlings across all years. By year 7, premium grade seedlings were 40 cm taller in height and 3.6 mm larger in BD than standard seedlings. Premium grade seedlings had similar height in year 5 to standard seedlings in years 6 and 7, and had similar BD in year 6 to standard seedlings in year 7. The largest tree was a premium grade seedling (526 cm height, 63.7 mm BD). Dieback in the shelterwood harvest was not affected by seedling grade or interaction with year, but was different among years (Table 3); dieback was highest in the first and fourth years after planting, and lowest in years 2 and 7 (Figure 2).

Seedling grade and interactions with year had no effect on understory dominance or free-to-grow status in the understory, but the main effects of year were significant (Table 3). Understory dominance and free-to-grow status was generally highest in the fifth growing season (78 percent and 83 percent, respectively), a year after competition control was implemented (Table 5). By year 7, approximately 70 percent of trees had dominance and were free-to-grow in the understory. Free-to-grow status in the midstory was not affected by seedling grade in any year (Table 3), and averaged 77 percent (±3.1) in year 3, 67 percent (±3.5) in year 5, and 59 percent (±3.7) in year 7.

Table 5. Least-squares means and associated standard errors for percent of trees dominant and free-to-grow in the understory canopy layer for northern red oak seedlings planted in a shelterwood harvest. Means followed by the same letters are not significantly different.

Year	Understory Dominance			Free-to-Grow in Understory		
1	53	4.2	bc	78	2.8	ab
2	46	5.0	c	69	3.2	bc
3	38	5.1	c	65	3.5	c
5	78	4.2	a	83	2.7	a
7	67	3.6	ab	72	3.4	bc

4. Discussion

We found support for our first hypothesis. The two grades were different in all nursery characteristics examined, and RCD was the best indicator of height and number of FOLR for both grades. Our results support previous studies that found RCD was a strong indicator of both nursery seedling root and stem morphology [15,25,48], and would be a practical visual standard for nurseries to use in their grading practices [18,32]. Although not tested directly in this study, RCD in the nursery has correlated strongly with subsequent seedling field performance of northern red oak [25,48,49] and was a good indicator of both belowground and aboveground tree attributes [50]. Previous studies found that root system morphology was more strongly correlated to field performance than RCD [25,49,51], but seedling grading using differences in root morphological characteristics would be impractical for most commercial nurseries that process thousands of seedlings. We found that improvements in FOLR number through visual grading was not as large as either RCD or height, consistent with another study [15] indicating visual grading will mostly improve RCD and height of planted seedlings. Although not a limiting factor in this study, grading by height may be especially important in areas with high deer populations that repeatedly browse seedlings and can lead to planting failures [22,52].

The weaker correlations within the two seedling grades compared to the random sample were due to the lack of inclusion of cull seedlings, concurring with Clark and others [15]. Each grade had relatively high variability and ranges in seedling size characteristics, indicating the inherent nature of variability of oak in the nursery [15,16,53] and the deficiencies of a visual grading process. Variability within each grade is probably representative of real-world conditions for nurseries that offer graded seedlings at an increased cost [15]. A potential bias in this study was the fact that the random sample did not have the largest seedlings represented. Because of this discrepancy, we are probably slightly overestimating gains in size made due to grading.

Our second hypothesis was partially supported, and we noted improved efficiency in planting efforts through grading. A two-year gain in height and a one-year gain in BD would have been achieved by planting only premium seedlings, and height (40 cm), and BD (3.5 mm) differences between grades in year 7 in the shelterwood harvest stand was statistically and biologically meaningful. These results indicate important gains can be made through a more intensive grading procedure than is normally performed at commercial tree nurseries and that has been previously recommended, primarily for plantings in the midwestern USA [19,23,29]. This supposition is also supported by a previous study that culled northern red oaks at rate of 50 percent, resulting in seedlings 80 cm tall and 7.1 mm in BD, but seedlings were not large enough to be competitive on productive sites in the Blue Ridge Mountains of the southeastern USA [20].

Numerous studies have found height or diameter gains through grading for northern red oak planted in regeneration harvests [23,25,33], but the use of such large bare-root stock, as in this study, provides a new approach to an old research question. If we used the lower 95 percent confidence limits from each nursery variable for the standard and premium grade trees as a minimum cull criterion, we would cull 77 and 94 percent of trees from our random sample, respectively. While this high cull rate would increase costs associated with nursery production, the resulting seedlings would be more uniform and more predictable in field performance [19,29]. In practice, managers could refine planting prescriptions by increasing tree spacing and selecting targeted planting areas to offset the increased costs of seedlings [23].

Our second hypothesis was partially rejected because grades did not differ in competitive abilities, exhibited by dominance and free-to-grow status in both the understory and the midstory. We could not find any studies that tested visual grading effects on competitive abilities, but larger stock types (e.g., container seedlings, 2–0 nursery seedlings) were more competitive than smaller stock types (e.g., 1–0 nursery seedlings) in numerous studies [19,21,50,54]. We were somewhat surprised that a year by grade interaction was not significant for understory dominance or free-to-grow status due to our competition control treatment conducted in year 4 after planting. However, we treated all seedlings, regardless of size, and this may have also helped equalized dominance and free-to-grow status between seedling grades. Competitive abilities in this study were probably also affected by an exceptional drought that occurred just following planting [55]. The drought was classified as abnormally dry to moderately dry from the time of planting for the next 2.5 months, and then worsened to severely dry to exceptionally dry for the following 7.5 months [55]. Seedling size advantages have been shown to dissipate under severe moisture stress due to the inability of larger seedlings to maintain root systems [50,56]. The drought probably caused the heavy mortality and lack of growth for the first three to four years after planting, and perhaps diminished competitive advantages of premium grade seedlings.

We found partial support for our third hypothesis. Our results indicate that visual grading was not beneficial to survival in the midstory-removal stand, and was only marginally beneficial to total BD and total height. Seedlings did not grow appreciably in height in this stand, and premium seedlings actually lost height due to dieback. Previous studies have also found negligible growth under low light conditions for northern red oak [21,33,57,58]. In contrast, black oak (*Q. velutina* Lam.) and white oak (*Q. alba* L.) were able to grow significantly in height (~20 cm) seven years after a midstory removal treatment in a northern Cumberland Plateau forest [14], and midstory removal has been successful in European studies where northern red oak was naturalized [9]. Underplanting success in midstory removal treatments may depend on specific site conditions, weather phenomena (*i.e.*, drought) that fluctuate yearly, seed source/genetics and quality of seedling. Regardless, data from multiple studies suggest height growth of planted oaks will be slow after several growing seasons in this silvicultural prescription (<25 cm) [14,33,35,58].

We did not find support for our fourth hypothesis because grades did not differ in planting shock, assessed from stem dieback and mortality in the early years following planting [28]. This finding was surprising given multiple studies that found increased transplant shock for larger seedlings [25,26,28,56]. However, we were approaching significance in survival differences between grades in the shelterwood harvest stand in year 2 (premium grade = 74 percent ± 3.6 *versus* standard = 64 percent ± 3.9), and in stem dieback in the midstory removal stand across years (premium grade = 23 percent ± 2.2 *versus* standard 17 percent ± 2.1). These results indicate that other factors we did not empirically test were probably acting as more important mechanisms affected planting shock. In particular, the exceptional drought probably caused dieback, inhibited growth, and increased mortality of seedlings from both grades, because average size of trees from both grades was relatively large. Previous studies have found drought negatively impacted larger trees more than smaller trees, but their seedlings sizes were much smaller than in this study [25,56]. Perhaps, the lack of inclusion of cull seedlings in both grades also equalized response to planting shock. Dieback and mortality was also impacted by unknown factors as evidenced by the fact that both stands exhibited relatively high dieback in years 4, 5, and 6, after which trees should have recovered from transplant shock and drought [26,28]. Frost events, although not directly observed in this study, may have negatively affected seedlings [59].

5. Conclusions

The potential for recruitment of oak into the next generation in these two stands was improved through intensive artificial regeneration methods that included heavy culling of nursery seedlings through visual size grading. Results indicated that visual grading would be best achieved through identification of RCD or height because they correlated well with each other and to the FOLR number. Management of oak on productive sites in the eastern United States, like the sites in this study, will require changes to accepted planting prescriptions for seedling size (*cf.* [18,29,30]) if trees are to compete with fast-growing yellow-polar and maple [20]. We found that seedling uniformity and overall size were improved through a stringent visual grading criterion that has only received limited testing prior to this study [34].

Grading had only minimal effects on seedlings in the midstory removal stand. If harvested now, the midstory removal would have a substantial number of seedlings from both grades deemed acceptable as advanced oak reproduction (e.g., >1 m height and >12 mm BD) that are predicted to be competitive [4,18,29]. Planting seedlings following harvesting may be more efficient than planting in a midstory removal stand, however, to avoid damage and mortality following planting [33,35]. Grading significantly improved size of seedlings in the shelterwood stand, and a two-year gain in height was achieved by planting premium compared to standard grade seedlings. Despite the drought, the majority of planted seedlings in both grades were competitive after seven growing seasons. While not empirically tested, the competition control in year 4 probably improved competitive abilities.

Our results are somewhat limited because we used only one genetic family and because of a lack of replication on other sites. However, confounding of seedling quality with genetics or seed source can make inferences from studies impractical, so we feel our results do have practical value [26,60]. Our inferences should be confirmed through additional studies and development of dominance probabilities [4,19]. Of particular interest will be to explore mechanisms controlling competitive ability, such as species and regeneration sources of competition, amount of light available to individual seedlings, and seedling size at planting.

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Author Contributions

Stacy L. Clark conceived and designed the experiment with input and expertise from Scott E. Schlarbaum and Callie J. Schweitzer; Stacy L. Clark designed field collection protocols and performed statistical analysis of data. Scott E. Schlarbaum contributed experimental materials and infrastructure for seedling processing. Stacy L. Clark wrote the paper.

Conflicts of Interest

The authors declare no conflict of interest.

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