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Impacts of deer herbivory and visual grading on the early performance of high-quality oak planting stock in Tennessee, USA

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Abstract

The growth of outplanted high-quality 1-0 northern red oak (*Quercus rubra* L.) seedlings, growth differences between two categories of visually graded seedlings and herbivory by white-tail deer (*Odocoileus virginianus* (Boddaert)) were examined after two growing seasons. Seedlings were planted in plots receiving three overstory treatments (high grade, commercial clearcut, and two age) and an uncut control on productive sites of the East Gulf Coastal Plain in Tennessee. Sixty seedlings were outplanted within each of 12 0.81-ha treatment units, resulting in three replicate blocks of the four treatments. Initial height, root-collar diameter and number of first-order lateral roots were recorded for each seedling prior to planting. Seedlings were visually graded into one of two categories (premium and good) based on morphological characteristics. Planted seedlings were measured at the end of the 2002 and 2003 growing seasons. Mean seedling survivorship after two growing seasons was 94, 92, 87 and 58% ($P < 0.001$) for the commercial clearcut, two-age, high grade and uncut control units, respectively. Differences in seedling height growth were found between the harvested units and uncut control units along with a significant interaction between overstory treatment and site ($P = 0.03$). Differences in seedling height were not significant among treatments involving harvest. After two growing seasons, seedlings graded as premium had produced 9 cm more height growth on average than seedlings graded as good ($P = 0.002$). In addition, seedlings browsed heavily during the 2002 and 2003 growing seasons were, on average, 36 cm shorter ($P < 0.001$) than unbrowsed seedlings. A significant level of mortality and diminished growth in the uncut control units suggests that pre-harvest enrichment planting without manipulating the overstory may not be a viable management option. Results from this study suggest a simple visual grading of seedlings prior to planting can result in significant growth gains early in the development of the seedlings. Further, the use of larger planting stock may have the added benefit of reducing the impacts of deer herbivory.

Keywords: Enrichment planting; White-tail deer; Herbivory; Visual grading; Oak seedlings; Oak regeneration; Tennessee

1. Introduction

Oak (*Quercus* spp.) replacement remains as a major obstacle to quality hardwood management despite the rich literature concerning silvicultural treatments for enhancing the natural regeneration of oak. This is especially the case on high quality or mesic sites where aggressive pioneer species colonize following disturbance (e.g. harvest). Oak replacement is also exacerbated by certain current harvesting techniques, such as high-grading. For example, northern red oak (*Q. rubra* L.), a mesophyte, is typically viewed as vulnerable to successional displacement by shade-tolerant non-oaks (Crow, 1988; Loftis, 1990a; Nowacki et al., 1990; Lorimer, 1993) and high-grading can mediate accelerated displacement. Large wildfires following complete overstory removal (Abrams, 1992; Lorimer, 2001), the loss of American chestnut (*Castanea dentata* [Marsh.] Borkh.), the use of fire by Native-Americans (Delcourt and Delcourt, 1998), and regional stand development patterns (Oliver, 1981; Clatterbuck and Hodges, 1988) all appear to have contributed to the recent dominance of oak throughout the eastern deciduous forest. However, many of the conditions favorable to the regeneration of oak are no longer present (Loftis and McGee, 1993), and many appear unlikely to be regained. The persistence of this challenge, however, does not necessarily reflect the lack of a biological solution. For example, Loftis (1983, 1990b) demonstrated that intermediate operations, such as basal area reductions through midstory

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removal, can help maintain oak as a major component of post-harvest stands. The shelterwood approach used by Loftis is based on the knowledge that the regeneration of oak is a process and not an event (Johnson et al., 2002), and that abundant large advance oak reproduction must be present before overstory removal (Sander, 1971).

Although a biological solution appears to exist (Loftis, 1990b), constraints imposed by social and economic factors render it unacceptable to many non-industrial private forestland (NIPF) owners. Many NIPF owners rely on short-term economic considerations to dictate forestland management decisions, including harvest timing. This tendency does not usually allow for the pre-harvest planning necessary to ensure an adequate advance oak reproduction population. Moreover, a change in NIPF tendencies is not expected due to the pressures of mostly economic constraints. Therefore, a post-harvest approach to establishing oak reproduction may be attractive in some situations. Knowledge gaps in the use of artificial hardwood reproduction still exist, however, particularly regarding early establishment and investment returns.

Direct seeding, containerized seedlings and standard bare-root seedlings have all been used in a variety of research designs investigating silvicultural options for oak regeneration (Johnson et al., 2002). Results have been mixed and success difficult to attain. Direct seeding options appear to be viable only in afforestation settings where there is little to no arborescent competition. Slow juvenile growth of oaks prohibits successful competition with stump sprouts and/or large advance reproduction of other species. In addition, invading shade-intolerant species such as yellow-poplar (*Liriodendron tulipifera* L.) or sycamore (*Platanus occidentalis* L.) can rapidly colonize and dominate a site. Both containerized seedlings and standard bare-root stock have been employed in post-harvest settings, but have proven unsuccessful in many cases (Hilt, 1977; Loftis, 1979; McGee and Loftis, 1986) due to competing forms of reproduction such as sprouting, especially when site productivity is high (Olson and Hooper, 1972; Russell, 1973). In addition, competition from non-native invasive (NNI) plants and herbivory from whitetail deer (*Odocoileus virginianus* (Boddaert)) have impeded artificial regeneration success (Gottschalk and Marquis, 1983; Gordon et al., 1995; Buckley et al., 1998; Oswalt et al., 2004).

Whitetail deer experienced significant population increases through the 20th century and are now the most abundant wild ungulate on the North American continent (Russell et al., 2001). Concomitantly, deer browsing has profoundly impacted both the composition and structure of many plant communities, including the depression of natural (Rooney and Waller, 2003) and artificial (Buckley et al., 1998) oak regeneration. In addition, deer herbivory can result in increased seedling mortality (Buckley et al., 1998) and significant impacts on height growth (Oswalt et al., 2004). The aggregate effect is the reduced competitive capacity of planted oak seedlings. Planting large and vigorous seedlings, i.e., high-quality seedlings, is one alternative to eliminate or reduce deer herbivory. Inherent in the idea of a tree shelter, a common management strategy to combat herbivory, is the assumption that a seedling will reach a height in which the probability of adverse impacts is significantly lessened. Planting taller seedlings may provide similar benefits.

The use of high-quality oak seedlings as nursery-grown advance reproduction has been discussed as a viable option for maintaining an oak component on highly productive sites (Kormanik et al., 1995; Kormanik et al., 2001) that might otherwise experience oak replacement with common management practices. Currently no published information exists on the possible benefits of adopting this approach outside of agronomic or afforested environments. This research investigated survival and growth of nursery-grown, high-quality seedling stock in a post-harvest setting. The study objectives were: (1) to examine seedling growth and survival differences of outplanted, high-quality 1-0 northern red oak (*Quercus rubra* L.) seedlings after two growing seasons among three common forest harvesting practices (high grade, commercial clearcut, two age) and an uncut control; (2) to compare the growth of two different seedling grades graded with a visual grading system based on easily measured morphological characteristics; and (3) to document potentially important impacts of deer browsing on outplanted seedlings. Our focus was on highly productive sites, such as found in the southern Appalachians and on sites of the gulf coastal plain, where regenerating oak has proven most difficult. Northern red oak seedlings were chosen because high-quality planting stock was available from the University of Tennessee Tree Improvement Program (Schlarbaum et al., 1998) and mature northern red oak was located on site (Table 1).

2. Material and methods

2.1. Study site

The study was conducted on the Ames Plantation in southwest Tennessee, along an intermittent stream in the headwaters region of the North Fork of the Wolf River (NFWR) (35°09′ N, 89°13′ W). The site encompasses approximately 80 acres of mixed hardwood forest dominated by various oak species and is part of the Southeastern Mixed Forest Province (Bailey, 1995). Two distinct landforms were identified within the immediate study site: an abandoned minor bottom near the confluence of the stream with the NFWR and ancestral terraces of the stream (Hodges, 1997). Changes in local hydrology have precluded these sites from the influence of flooding.

The headwaters region of the NFWR is located within the Mississippi Embayment of the Gulf Coastal Plain. The geology is dominated by the highly erodible Wilcox and Claiborne formations of Tertiary age exposed by the erosion of Quaternary and Tertiary fluvial deposits and the overlying Pleistocene loess deposits common in western Tennessee (Safford, 1869; Fenneman, 1938). The principal soil groups are Grenada-Loring-Memphis on the terraces and Falaya-Waverly-Collins within the minor bottom (USDA, 1964). Site index (base age 50 years) was estimated to be 75 for oaks, 85 for yellow-poplar, and 70 for sweetgum (*Liquidambar styraciflua* L.) on both sites. Average age for the dominant and co-dominant stems across the study site was 70 years. Estimates of

Table 1
Pre-harvest importance values[a] for common species of the three experimental blocks within the oak regeneration study on Ames Plantation, Fayette County, Tennessee

Species	Experimental block		
	East	West	Bottom
Acer negundo			16.98
Acer rubrum		6.24	4.08
Betula nigra			7.27
Carya tomentosa	6.09	18.21	4.73
Cercis canadensis			4.08
Cornus florida	10.32	15.52	8.13
Diospyros virginiana			6.28
Fraxinus pennsylvanica	11.26		
Juglans nigra	14.27	15.85	
Juniperus virginiana	11.34		
Liquidambar styraciflua	17.49	22.08	49.58
Liriodendron tulipifera	26.92	28.64	95.49
Maclura pomifera			4.09
Morus rubra	8.62	4.99	4.03
Nyssa sylvatica	9.10		
Platinus occidentalis			4.49
Prunus serotina	6.35		
Quercus alba	17.02	82.32	5.57
Quercus falcata	77.60	18.30	9.85
Quercus pagoda	20.48	6.64	27.47
Quercus rubra		19.90	
Quercus stellata	42.48	44.36	
Quercus velutina			5.52
Sassafras albidum	9.25	10.21	
Ulmus alata			15.90
Ulmus americana	11.41	6.74	21.91
Ulmus rubra			4.55

[a] Sum of relative dominance, relative density, and relative frequency (Curtis and McIntosh, 1951).

local deer density on the Ames Plantation for 2004 and 2005 were 35 deer square-mile^{-1} and 22 deer square-mile^{-1}, respectively (Christopher Shaw, unpublished data).

2.2. Study design

In the fall of 2001, three experimental blocks were identified based on landform and position. Significant differences in average stand basal area ($P = 0.04$) were found among the blocks and appeared to be a result of past selective cutting. Twelve 0.81 ha treatment units were designated within three experimental blocks with four units located within the abandoned bottom (Bottom block) and eight units located within the terrace sites upstream from the abandoned bottom (four each within the East and West blocks). All units were located on level ground with slope <1–2%. The East and West blocks are designated by the block position in reference to the stream dissecting the study site. Species composition at the time of establishment was dominated by oak species on the ancestral terraces and yellow-poplar and sweetgum in the Bottom block. Importance values (Curtis and McIntosh, 1951) were calculated for the common midstory and overstory species located within each block (Table 1).

Three overstory treatments (high grade, commercial clearcut, and two age) and an uncut control were randomly assigned to the 4 units within each of the three replicate blocks using a randomized complete block design. Harvesting for all treatments was completed in the winter of 2001–2002. The commercial clearcut involved the removal of all stems greater than 15 cm diameter at breast height (dbh). This treatment was designed to represent a common practice on industrial forestland in west Tennessee. The high grade treatment was a standard diameter limit cut where all stems greater then 35.5 cm dbh were removed and was designed to represent a common and persistent practice on NIPF lands. The two-age treatment involved retaining a stand basal area of approximately 1.85–2.47 $m^2\ ha^{-1}$ (15–20 $ft^2\ acre^{-1}$). Residual stems were chosen based on both the desire to leave stems of desirable species with an opportunity to increase in value and to have stems evenly distributed throughout the stand. Desirable species included oaks, hickories (*Carya* spp.) and yellow-poplar. One uncut control was assigned to each block for comparison with treated units.

2.3. Seedlings

Seedlings originating from two genetic families (families 321 and 234) in a seedling seed orchard on the Ames Plantation (Schlarbaum et al., 1998) were planted following harvest. The seedlings were grown at the Georgia Forestry Commission's Flint River Nursery under fertilization and irrigation protocols developed by Kormanik et al. (1994a). The seedlings were lifted in February 2002 and were graded using procedures developed by Kormanik et al. (1994a,b), as modified by Clark et al. (2000). The seedlings were measured for height and root collar diameter (rcd), the number of first-order lateral roots (folr) *sensu* (Ruehle and Kormanik, 1986), and were visually classified into one of three categories (cull, good, and premium as defined by Clark et al., 2000). Thirty seedlings from the good and premium classes were randomly chosen from each family and shovel planted (6.1 m × 6.1 m) in March 2002 within each of the 12 units. A total of 720 seedlings (i.e. 30 seedlings × 2 families × 12 units) were planted. End-of-season survival and growth (height and rcd) were obtained in January 2003 and January 2004 for all seedlings. Natural regeneration density following two growing seasons was quantified with a nested plot design consisting of one 0.0004 ha (milacre) plot nested within a 0.004 ha (0.01 acre) plot. Four nested plots were located systematically within each of 12 study units for a total of 48 nested plots (48 0.0004 ha plots and 48 0.004 ha plots). Natural woody regeneration was recorded by species into one of four height classes: (1) <31 cm, (2) ≥31 < 61 cm, (3) ≥61 < 122 cm, and (4) ≥122 cm. Stems within height class 1 were recorded using the 0.0004 ha plots and stems in height classes 2, 3 and 4 were recorded using the 0.004 ha plots.

2.4. Herbivory

A "browse pressure classification" after Buckley (2001) was used to investigate the effects of deer herbivory on planted seedlings. Browse pressure was classified into one of four categories: no browse, terminal browse, lateral browse and complete browse. No browse was defined as no visible signs of herbivory; lateral browse was defined as herbivory limited to lateral shoots only; terminal browse was herbivory limited to only the terminal shoot; and complete browse was defined as observed herbivory on both lateral and terminal shoots.

2.5. Analysis

Mean seedling height growth, rcd growth, browse pressure and seedling survivorship were analyzed for main and interactive effects of overstory treatment, seedling quality class (grade), genetic family, and terminal shoot removal using mixed effects ANOVA models and post-ANOVA mean separation using Fisher's Least Significance Difference Procedure (SAS Institute Inc., 1989) with an error level of $\alpha = 0.05$ to indicate significant differences. Mean overall natural regeneration density and density within each height class were analyzed in the same manner to detect differences among treatments. Survivorship data were converted from a binary variable to a proportional variable at the sub-unit level in order to satisfy normality assumptions and to include interaction terms in the subsequent ANOVA models. In addition, a binary variable called "terminal shoot removal" (TSR) was created by combining the complete browse and the terminal browse categories. This variable allowed consolidation of seedlings where terminal shoots were browsed and allowed testing for differences in seedling height growth between single and multiple browse events. Logistic regression and chi-square analyses were used to explore the possible relationship between seedling height before bud break and the probability of TSR and to determine the limiting height for browse.

3. Results

Post harvest basal area of material greater than 15 cm averaged 0, 3.2, 4.6 and 32.6 $m^2 ha^{-1}$ for the commercial clearcut, two-age, high grade treatments and uncut control, respectively. Mean initial rcd (referred to as ground line diameter following planting), initial shoot height, and number of folr were all greater for premium seedlings (Table 2). Families were similar; therefore analyses of initial seedling morphology used pooled data. Seedling survivorship was lower in the uncut control units following the 2002 and 2003 growing seasons ($P < 0.0001$, 0.001, respectively) than it was in the harvested units. No significant interactions were identified. Mean seedling survivorship following the first growing season was 100, 95, 95, and 67% for the commercial clearcut, two-age, high grade, and uncut control units, respectively. After two growing seasons seedling survivorship decreased to 94, 92, 87, and 58%, respectively (Fig. 1). Herbivory by whitetail deer had no significant influence on seedling survivorship through two growing seasons. Additionally, no differences in survivorship were identified between seedling quality class and genetic families.

At the end of two growing seasons (2002 and 2003), the average height growth of the northern red oak seedlings was affected by the overstory treatments and seedling grade. Average growth after two growing seasons tended to be higher in the harvest treatments. However, this result is dependent upon block (block × overstory treatment interaction, $P = 0.03$; Fig. 2). Specifically, height growth was significantly greater for the two-age and commercial clearcut treatments only in the west block. In addition, height growth was much lower for the high grade and two-age treatments only in the bottom block. Two-year height growth averaged across block was 35.78, 34.83, 28.88, and 26.18 cm in the commercial clearcut, two-age, high grade and uncut control treatments, respectively. Height growth was greater for planted seedlings graded as premium ($P = 0.002$). Mean seedling height growth for premium seedlings was 38.13 and 29.35 cm for seedlings graded as good. No interactions involving seedling quality

Table 2
Mean root collar diameter, mean initial height and mean number of first-order lateral roots for each family and quality class of outplanted northern red oak (*Quercus rubra* L.) seedlings prior to planting in March of 2002 for the oak regeneration study on the Ames Plantation, Fayette County, Tennessee

Family #		Good		Premium		All	
		Mean	*N*	Mean	*N*	Mean	*N*
234	Root collar diameter (mm)	10.65	240	12.83	120	11.74	360
	Initial height (cm)	102.28	240	120.00	120	111.14	360
	First-order lateral roots	15.79	240	21.08	120	18.43	360
321	Root collar diameter	9.81	264	12.26	96	11.04	360
	Initial height	105.42	264	128.60	96	117.01	360
	First-order lateral roots	17.13	264	21.91	96	19.52	360
All	Root collar diameter	10.23	504	12.55	216	11.39	720
	Initial height	103.85	504	124.30	216	114.07	720
	First-order lateral roots	16.46	504	21.49	216	18.98	720

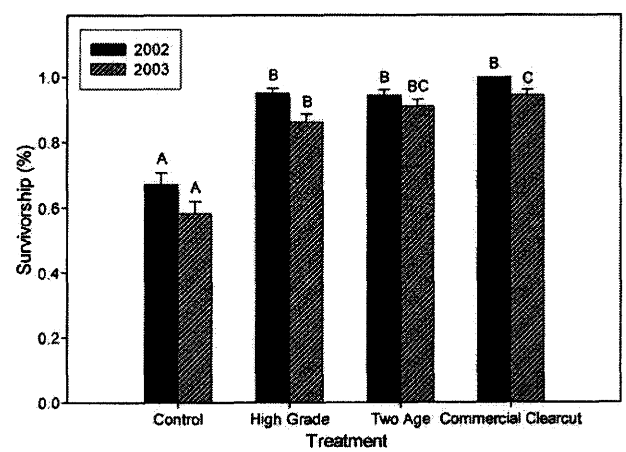

Fig. 1. One and two-year survivorship (%) of planted northern red oak (*Quercus rubra* L.) seedlings under four overstory treatments in Fayette County, Tennessee. Different lettering indicates a significant difference ($P < 0.05$) between treatments analyzed separately by year.

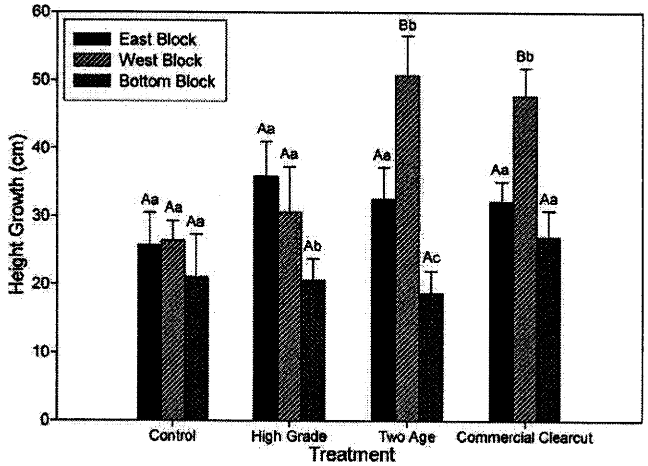

Fig. 2. Two-year height growth (cm) of planted northern red oak (*Quercus rubra* L.) seedlings under four overstory treatments and on three sites in Fayette County, Tennessee. Error bars represent 1 standard error. Different lettering indicates a significant difference ($P < 0.05$) within treatments (a) and between treatments (A).

(i.e. block × quality $P = 0.43$, treatment × quality $P = 0.69$, block × treatment × quality $P = 0.21$) were significant.

Two-year ground line diameter (GLD) growth was affected by harvest treatment and seedling quality ($P < 0.0001$ and $P = 0.019$, respectively). Pairwise comparisons indicated all harvest treatment comparisons differed (Fig. 3) at the alpha 0.05 level. No significant interactions were identified. GLD growth for the uncut control was negative due to dieback and resprouting. GLD growth was 4.5 times greater for seedlings in commercial clearcuts as compared to "no" growth in the uncut control, 3.5 times greater for seedlings in the two-age treatment as compared to the uncut control and 3 times greater for the high grade treatment as compared to the uncut control. Mean GLD growth for seedlings graded as premium was 3.5 mm, and 2.6 mm for seedlings graded as good. No differences in height or GLD growth were found between genetic families.

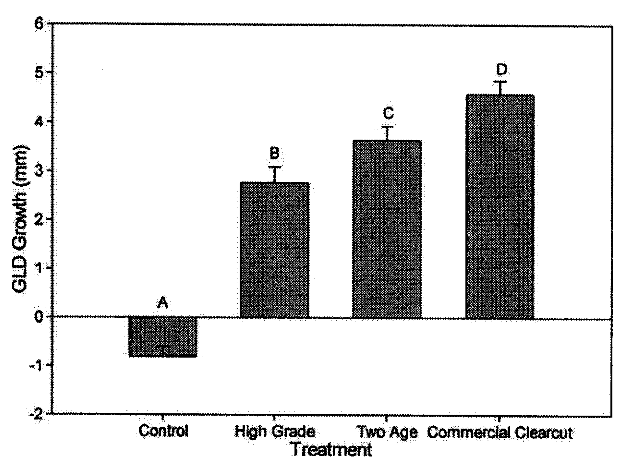

Fig. 3. Two-year ground-line diameter (GLD) growth of planted 1-0 northern red oak (*Quercus rubra* L.) seedlings among four treatments for the Oak Regeneration Study at the Ames Plantation, Fayette County, Tennessee. Different lettering indicates a significant difference ($P < 0.05$) between treatments.

Seedlings experienced browse pressure during both growing seasons. Seedlings exhibited signs of TSR following the 2002 growing season ($n = 104$, 18% of surviving seedlings), 2003 growing season ($n = 58$, 10%) and both growing seasons ($n = 76$, 12%), irrespective of overstory treatment. However, many seedlings did escape TSR in both 2002 and 2003 ($n = 355$, 60%). Mortality, primarily in the control units, accounted for 127 seedlings. Deer herbivory through TSR influenced 2-year height growth ($P < 0.0001$). Mean height growth was greatest for seedlings that did not exhibit signs of TSR and mean 2-year height growth was least for seedlings that exhibited signs of TSR following both growing seasons (Table 3). Therefore, seedlings that experienced TSR in both 2002 and 2003 were, on average, 36 cm shorter than seedlings exhibiting no signs of TSR. Terminal shoot removal did not occur on any seedlings greater than 148 cm initial planting height (which comprised 5% of the population planted) during the 2002 growing season. Following the 2003 growing season, 47% of the seedlings had surpassed the 148 cm "browse-line". Consequently, logistic regression analysis of pooled seedling data (pooled across treatment) suggested that dormant season seedling height influenced TSR in both 2002 and 2003 ($P < 0.0001$, 0.0001, respectively).

Naturally regenerated woody species density (stems hectare^{-1}) did not differ among the three harvest treatments ($P = 0.4104$) or across four height classes ($P = 0.3702$, 0.2560, 0.1959, 0.3410 for height classes 1, 2, 3 and 4, respectively). Therefore, mean density was calculated from pooled data across the harvest treatments. Following two growing seasons, mean density of naturally regenerated woody species was 8303, 5261, 3154 and 1626 stems ha^{-1} for height class 1, 2, 3 and 4, respectively (Table 4) within the harvested units only. The most prevalent species was yellow poplar with an average of 353 stems ha^{-1} in the greater than 122 cm class. Mean density of planted oak seedlings was 0, 2, 67 and 173 stems ha^{-1} for height class 1, 2, 3 and 4, respectively. Yellow poplar was the only species with larger mean density in the largest height class. Planted oak seedlings combined with natural oak reproduction accounted for an average of 237 stems ha^{-1} in the greater than 122 cm height class, second only to the density of yellow poplar. The combined species category (other) had the greatest number of stems in all height classes. However, based on present overstory species dominance at the Ames Plantation, these stems are not expected to compose a major portion of the overstory in the future.

Table 3
Season of occurrence, number (N), mean height growth and associated standard error of northern red oak (*Quercus rubra* L.) seedlings with observed Terminal Shoot Removal (TSR) pooled across treatments within the oak regeneration study on Ames Plantation, Fayette County, Tennessee

Season	N	Mean (cm)	S.E.
2002	104	34.21 a	2.68
2003	58	10.10 b	2.78
2002 and 2003	76	4.67 b	2.13
No TSR	355	40.72 c	1.71

Different lettering (a, b) indicates differences ($P < 0.05$).

Table 4
Stems hectare^{-1} estimates for planted oak seedlings, natural reproduction of the most dominant species and other potential overstory species following two growing seasons within harvested units[a] of the oak regeneration study on Ames Plantation, Fayette County, Tennessee

Height Class	Planted oak		Yellow poplar	Red maple	Oak spp.[b]	Other[c]
	Time of Planting	2004	2004	2004	2004	2004
<31 cm	0	0	2409	1097	1717	3080
≥31 < 61 cm	0	2	1413	571	764	2513
≥61 < 122 cm	205	67	996	255	193	1710
≥122 cm	62	173	353	94	64	1115

[a] Data do not include uncut controls.
[b] Oak species include: *Q. alba*, *Q. falcata*, *Q. michauxii*, *Q. pagoda*, *Q. phellos*, *Q. prinus*, *Q. rubra*, *Q. stellata*, and *Q. velutina*.
[c] Other species include: *Acer negundo*, *Carya* spp., *Fraxinus pennsylvanica*, *Juglans nigra*, *Liquidambar styraciflua*, *Nyssa sylvatica*, *Platinus occidentalis*, *Prunus serotina*, *Sassafras albidum*, and *Ulmus* spp.

4. Discussion

4.1. Seedling survivorship

One and two-year survival of planted seedlings was greater than 87% following two growing seasons in all treatments except the uncut control units, which experienced high mortality rates in both 2002 and 2003. Several factors could have contributed to the mortality in the no-cut treatment: browse pressure, poor seedling planting procedures, high levels of shade or a combination of factors. Poor planting procedures were probably not a critical factor because mortality would have been observed throughout the study. Survivorship was significantly lower in the uncut control treatment only (Fig. 1). Similarly, browse pressure did not appear to be a factor in subsequent analyses. Although no photosynthetically active radiation (PAR) measurements were taken in this study, Johnson et al. (2002) reported that light levels of dense canopies often fall below 2% of full sunlight. The intact canopies of the no-cut treatment produced dense high overstory shade. Therefore, reduced light availability is probably the major contributing factor to the observed mortality of seedlings in the uncut control treatment. These data suggest that pre-harvest enrichment planting without basal area reductions might not be viable due to unacceptable mortality rates. In contrast, much less seedling mortality occurred in the more open light environments created by the three harvest treatments.

4.2. Harvest treatment effects

Following two growing seasons, complex height growth patterns among the implemented treatments are beginning to emerge. Specifically, height growth was greater in the commercial clearcut and two-age treatments only in the west block (Fig. 2). The block × treatment interaction was statistically significant. Site indices for red oaks did not differ among the three blocks. Therefore, site productivity differences do not appear to exist. Oswalt et al. (2004) reported differences in herbaceous competition among the block × treatment combinations. Therefore, block differences may be the result of differences in the herbaceous response (Oswalt et al., 2004) and therefore, herbaceous competition. Ground-line diameter growth was more straightforward than height growth. GLD growth increased with decreasing residual basal area.

Although the block × treatment interaction term was significant in the height growth analysis, the overall trend among treatments suggested greater growth in the cut treatments. The trend is slightly weakened by the fact that the majority of height growth observed within the uncut control treatments was etiolated (Oswalt et al., 2003), and therefore not directly comparable to the growth in the three harvest treatments.

After two growing seasons no differences in the density of woody species natural reproduction were detected among the three harvested treatments. Species-specific overall density for natural reproduction was highest for yellow poplar, followed by red maple (*Acer rubrum* L.) (Table 4). When the planted oaks are aggregated with the naturally regenerating oaks, mean oak density in the largest height class is greater than red maple natural reproduction but less than yellow poplar. The remaining natural reproduction is unlikely to be a major component of the future stand. One purpose of planting the high quality oak seedlings was for enriching the site with oak seedlings in order to increase the likelihood of oak stems remaining in the regenerated stand. Planting tall high quality oak seedlings has increased the number of oak seedlings in the largest height class after two years. No definitive statements can be made regarding the future success of the planted seedlings. However, after 2 years the seedlings appear to be in a viable position.

4.3. Planting stock

Research into the concept of "bigger is better" regarding oak planting stock has been discussed (Kormanik et al., 1995; Schlarbaum et al., 1998; Clark et al., 2000; Kormanik et al., 2001) and relationships between morphological characteristics of seedlings and subsequent field performance have been identified. Generally, studies have shown that larger seedlings (i.e. greater shoot heights, larger root-collar diameter and higher numbers of folr roots) attain greater heights (Ruehle and Kormanik, 1986; Teclaw and Isebrands, 1993; Kormanik et al., 1994b; Thompson and Schultz, 1995). Researchers continue to investigate precision seedling grading systems (Jacobs and Seifert, 2004). However, seedling grading by commercial nurseries is generally not based on precise measurements (Clark et al., 2000). Therefore, we posit that a visual grading system, such as presented by Clark et al. (2000) may be more pragmatic and useful. The 31% growth gain observed in the premium-graded seedlings over those graded as good in this study is further evidence supporting the advantages of visual grading. In addition, mortality in the larger premium seedlings was not observed and GLD growth was 35% greater in the premium seedling category than the seedlings graded as good.

4.4. Browse pressure

Herbivory pressure from whitetail deer is detrimental to the success of planted hardwood seedlings in plantations and enrichment plantings (Buckley et al., 1998; Castleberry et al., 2000; Opperman and Merenlender, 2000; Russell et al., 2001; Romagosa and Robison, 2003; Rooney and Waller, 2003). However, detailed quantification of the effects of deer herbivory on planted seedling height growth is limited. In addition, management suggestions for limiting deer herbivory have been mainly limited to tree shelters. Tree shelters are often cost prohibitive (Clatterbuck, 1999), leaving landowners with very limited options, if any at all. We posit that a simple solution is to plant larger seedlings. Logistic regression analyses presented in this study suggest that the initial planting height (or the height of the seedling at onset of bud-break) influences the probability of the terminal shoot being removed, and therefore impacts the height growth of the seedling. Planting seedlings that will surpass the "browse line" sooner or that are beyond that point at the time of planting will increase the likelihood of successful establishment. High-quality (larger and taller) seedlings will cost more than regular nursery-run conventional seedlings. In addition, culling a percentage of conventional seedlings through grading will increase overall establishment costs. However, increased seedling and planting costs of larger seedlings is much less than the cost of seedling shelters. Additionally, many of the seedlings, 23%, were already taller than 122 cm (the height of many common tree shelters) at the time of planting and approximately 72% of those in the harvested units were above that height after the second growing season.

Deer browse in the form of TSR seriously affected growth of planted seedlings. Seedlings that experienced TSR during both years of this study were on average 36 cm shorter than seedlings that did not. This represents an 89% loss of potential height growth. Additionally, herbivory can be highly variable (Table 2), with some years representing a much larger impact on seedling height growth than others.

After two growing seasons, heights of many seedlings (47%) have already surpassed the "browse line". These seedlings are beyond what could be considered a limiting height for deer browse in the habitats represented in this study. Where habitats are marginal, deer densities are extremely high, or changes in local weather or deer herd work to render habitats periodically sub-optimal, then browsing intensity may increase to a point where even larger seedlings would be more likely to be impacted as deer effort to browse seedling tops increases, perhaps pushing the seedling over. However, high-quality seedlings like those used in this study have a greater initial advantage overcoming deer herbivory, compared to commonly available seedling stock due to the larger initial planting heights. In addition, the taller seedlings exhibited better growth (see Planting Stock in Section 4).

5. Conclusion

The use of oak artificial reproduction by itself in highly productive systems may not be the complete answer. Using only high-quality oak seedlings is not the total answer either. Although seedling survival is high, deer herbivory and competition from natural regeneration preclude the mere planting of high-quality seedlings from being a panacea. However, the overall oak regeneration equation can be simplified with the use of high-quality oak seedlings. Results following two growing seasons indicate seedling survival is high (greater than 85% on harvested sites), problematic deer herbivory can be minimized by planting taller seedlings and utilizing a visual grading system can impart additional benefits in terms of seedling growth gains from both height and root-collar diameter growth. Johnson et al. (2002) state that each step of the oak regeneration process is plagued with difficulties and unknowns. The use of high quality seedlings for post-harvest enrichment planting may aid in reducing the number of necessary steps, unknowns, and difficulties in establishing a new cohort of oaks on these sites.

The results of the current study represent two growing seasons of growth and observations. Therefore, definitive statements may be premature. However, the establishment and early development of oak seedlings are critical steps to the success of any artificial reproduction effort. This study indicates that using a visual grading system improves planting stock and planting taller seedlings reduces the impact of deer herbivory. Post-harvest enrichment planting of high quality oak seedlings could prove to be a viable management alternative for enhancing the oak component on highly productive sites where naturally regenerating oak has proven difficult. High-quality oak seedlings used in this research have exhibited good growth and may aid in reestablishing oaks on this site.

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