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Eleven-Year Effects of Mechanical Site Preparation on Oaks Planted on Former Agricultural Fields

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Abstract: Mechanical site preparation is often prescribed as a tool for correcting soil condition problems encountered when planting former agricultural fields. While the impact of mechanical site preparation on early growth and survival of young oak seedlings is well-known, there is a shortage of information regarding the longer-term effects of these treatments. Four hundred and eighty, 1-0 bare-root seedlings each of Nuttall oak (*Quercus texana* Buckley), Shumard oak (*Quercus shumardii* Buckley), and swamp chestnut oak (*Quercus michauxii* Nutt.) seedlings were planted in February 2008 on a retired agricultural site in northwest Mississippi. Four site preparation treatments were utilized, with 160 seedlings of each species per species/mechanical treatment combination, totaling 1440 seedlings for the study. Mechanical site preparation included control, subsoiling, bedding, and combination plowing treatments applied on 3.1 m row centers. Eleven-year diameter (DBH), total height growth (HT), height-to-live crown (HTLC), and survival data were recorded in early 2019. Treatment effects were analyzed, and significant differences were not detected for tree survival. However, differences were observed in the DBH, HT, and HTLC averages of swamp chestnut oak and the DBH of Shumard oak.

Keywords: mechanical site preparation; retired agricultural fields; oak afforestation; self-pruning; hardwood plantations

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1. Introduction

Cost-share incentive programs, in conjunction with increased awareness of the ecological importance of forested bottomland ecosystems, have resulted in the establishment of millions of hectares of hardwood plantations in the Lower Mississippi Alluvial Valley (LMAV) over the past few decades. While the exact area of established LMAV hardwood plantations is not available, 149,798 hectares had been established in the LMAV by 2004 [1]. Predictions indicate afforestation of up to 10.1 million hectares of retired agricultural fields by 2040 [2]. This necessitates the development of successful establishment techniques for these new hardwood forests, which are expected to be oak (*Quercus* spp.)-dominant [3].

The survival and growth of planted oaks were insufficient in a substantial number of early afforestation efforts in the 1980s and 1990s [2]. These early results led to the development of appropriate planting techniques that, when employed, can be used to successfully afforest bottomland oak species. Acceptable seedling performance can be expected when quality seedlings are planted on appropriate sites undergoing necessary cultural and herbicidal treatments, with multiple early rotation studies observing planted bottomland oak survival rates above 80 percent [1,4–7].

The growth and survival of seedlings can be positively influenced by using quality stock and sound planting methodologies. Additional ameliorative benefits are often realized through the use of mechanical site preparation for areas with soil compaction problems. Many of the planting efforts over the last few decades have taken place on retired

agricultural fields, where soil compaction is often problematic on these sites due to prior land use [7]; a variety of mechanical site preparation treatments have been used to help correct these issues.

Subsoiling, bedding, and combination plowing have all been used in various site preparation efforts, with varying degrees of success. Subsoiling is performed by pulling a straight or parabolic shank with or without a winged tip through the soil at varying depths to fracture restrictive layers that limit nutrient availability and root penetration in compacted soils [8]. Planted seedling growth is improved from increased moisture availability and enhanced root development through increased ability to exploit soil nutrients, especially in low-moisture or low-fertility conditions [9,10]. These increases in root volume and rooting depth were documented [10], but was not observed in earlier work on oak seedlings grown in subsoiled areas that included trees from this study [11]. Statistical differences in three-year stem biomass measurements were not detected between seedlings grown in control and subsoil plots. However, research sites received above-average rainfall throughout the study duration, and the authors surmised that, under low-rainfall drought conditions, subsoiling and control treatments would have likely separated.

Improved early growth and survival for seedlings planted on retired agricultural areas receiving subsoiling treatments have been observed for a variety of species including Shumard oak (*Quercus shumardii* Buckley), water oak (*Quercus nigra* L.), willow oak (*Quercus phellos* L.), northern red oak (*Quercus rubra* L.), and green ash (*Fraxinus pennsylvanica* Marsh.), among others [3,10,12,13]. While the typical benefits of subsoiling to growth and survival are well-known, the three-year results involving seedlings grown on the site, detailed in this paper, differed from normal expectations, with no detectable differences between groundline diameter or height of three different oak species [4].

Bedding is accomplished using a plow or disk system to create a mounded planting site comprised of cultivated soil 1 to 2 m wide and 15 to 60 cm deep [14,15]. Site preparation, in the form of bedding, is often prescribed to elevate the root systems of planted seedlings above saturated or inundated soils in efforts to improve seedling survival [14]. The treatment was successfully utilized in pine silviculture [16], but, theoretically, its use on low-lying sites should prove even more beneficial for some species of hardwoods. Hardwood species are incredibly variable in flood tolerance, with species of greater commercial interest typically being less tolerant of poorly drained soils as well as flooding events [17].

Increased seedling growth has been documented in oaks planted on bedded sites due to improvements in soil drainage and aeration, incorporation of organic matter into the beds, and a degree of vegetative competition control [14,18,19]. Other research efforts showed that survival may be increased for Nuttall oak on bedded sites [14] by as much as 35 percent, but, overall, bedding results are inconclusive. An earlier report of oak performance at three years on this study site observed no difference in survival. However, greater height and groundline diameter (GLD) growth was exhibited in three-year-old Nuttall oak, Shumard oak, and swamp chestnut oak in bedded areas compared with subsoiled or control areas [20]. Two bedding studies in Missouri and Indiana did not result in detectible growth or survival differences for pin oak (*Quercus palustris* L.), swamp white oak (*Quercus bicolor* Willd.), or swamp chestnut oak [14,21].

Combination plowing involves using a tipped or untipped subsoil shank in conjunction with a bedding plow or disk blades in one equipment pass. The treatment serves to combine both subsoiling and bedding into one treatment. Combination plowing is intended to improve seedling growth and survival through improvement in soil compaction and drainage, as well as provide some short-term competition control. Use of combination plowing and its benefits to growth and survival are well-known in pine silviculture [22,23], but use of the treatment is relatively unexplored in hardwood establishment. Earlier observations of seedlings planted in this study, along with those on two other research sites, constitute most of the reported knowledge regarding combination plowing for mechanical site preparation in hardwood plantation efforts. These early results indicated that combina-

tion plowing results in greater seedling growth than subsoil-only or control plots, but did not differ compared with seedlings grown in bedding treatments [4,13,20].

Very little information is available regarding stem development of oaks grown under plantation conditions. Additional stems arising from natural sources of seed were expected during the plantation establishment efforts described in the opening paragraphs of this article. However, sufficient quantities of these stems have been lacking in most plantation efforts, resulting in lower than anticipated total densities as these stands mature [7,24]. Poor pruning is typically encountered as hardwood plantations age due to cost-driven low planting densities and lack of additional natural regeneration by light-seeded tree species [7,25]. Traditionally, branches on the lower bole of a tree are expected to prune early in stand development, resulting in a higher concentration of clear wood growth over time occurring at that position due to the absence of live branches. Subsequently, the greatest proportion of tree value forming in natural stands resides in butt logs [26]. Consequently, the lack of self-pruning and the persistence of lower-bole limbs raise concerns over the future value of these stands [24].

The early growth and survival results of trees measured in this study are reported in a previous volume of this journal [20]. The magnitude of treatment differences declined over time when considering the 11-year results described herein. Very little information exists regarding mechanical treatment effects on oak growth and survival more than five years after initial establishment. It is possible that early treatment effects should not be viewed as reliable predictors of future growth in hardwood planting efforts and more as indicators to ensure early survival. The objective of this study was to evaluate mechanical site preparation effects on growth, survival, and lower-bole self-pruning of three oak species on a retired agricultural site over 11 growing seasons post-planting.

2. Materials and Methods

2.1. Study Site Description

This study was conducted on a former agricultural field on the United States Army Corps of Engineers Arkabutla Lake Project approximately 11 km northwest of Coldwater, Mississippi (33.744° N, 90.078° W) at an average elevation of 76.2 m. Soybean (*Glycine max* (L.) Merr.) production occurred onsite through September 2007. The soils map as Collins/Falaya silt loam (coarse-silty, mixed, active, acid, thermic Aquic Udifluvents) and Richland silt loam (fine-silty, mixed, thermic Typic Fragiudalfs) [27]. These soils are moderately well-drained, and testing showed an average pH of 6.2 across the site at planting. Onsite precipitation was measured for the first three years after establishment and averaged 153.8 cm [20]. The average 30-year temperature is 16.2 °C, with temperature extremes ranging from −20.0 to 40.6 °C, and average precipitation over the course of this study has been 145.2 cm [28]. Dominant herbaceous species present at planting included Brazil vervain (*Verbena brasiliensis* Vellozo.), poorjoe (*Diodia teres* Walt.), and thorny amaranth (*Amaranthus spinosus* L.). Over 20 additional herbaceous species occurring in smaller quantities were also identified. The total ground coverage of all herbaceous species was approximately five percent.

A diverse vegetative complex germinated from the seedbank after afforestation occurred. However, initial onsite herbaceous vegetation was controlled using pre-emergent Bayer AG Oust® XP applications [4]. After canopy closure occurred between 2015 and 2016, very little herbaceous vegetation persisted in the shaded ground conditions created by the overstory canopy.

2.2. Treatments and Seedling Establishment

Four mechanical treatment options were utilized: control (no mechanical treatment), subsoiling, bedding, and combination plowing. Treatments were installed on 5 November 2007, using 3 m centers with an agricultural tractor. Subsoiling was performed using a Case IH no-till subsoiler system to a depth of 38 cm. Bedding was accomplished using an

agricultural furrow plow with disk blades set to form a soil bed 1 m wide and 20 to 25 cm deep. Combination plowing involved bedding over subsoil trenches.

Prior to budbreak, all treatment areas received a pre-emergent herbaceous weed control (HWC) application of Oust XP® over the top of all seedlings on 4 March 2008, in 1.5 m bands at a rate of 140.1 g product/hectare. A second application of Oust XP® was applied on 2 March 2009, over the top of one half of planted seedlings. A Solo® backpack sprayer was used for herbicide application, with a total spray volume of 93.5 L/ha. HWC treatments were considered in the statistical analysis; however, due to minimal effects on growth parameters, differences between chemical treatments are not reported in this manuscript.

Seedling specifications dictated 1-0 bare-root seedlings possess stems between 45.7 and 61.0 cm tall and root systems between 20 and 25 cm in length. In addition, root systems were to have a minimum of eight first-order lateral roots. A total of 1440 seedlings were planted, with 480 seedlings each of Nuttall oak, Shumard oak, and swamp chestnut oak. The study had 480 seedlings of each oak species (480 total = 160 per block = 40 per mechanical treatment). Seedlings were planted at root-collar depth with planting shovels on 12 February 2008, using 3.1 by 3.1 m spacing to give a seedling density of 1075 seedlings per hectare.

2.3. Measurements

Diameter at breast height (DBH), total height growth (HT), height-to-live crown (HTLC), and survival data were recorded in January and February 2019. DBH was measured 1.37 m above ground using a Spencer Products loggers' tape in $^1/_4$ cm increments. HT and HTLC were recorded in 0.3 m increments using a Haglof Vertex III hypsometer. HT was measured to the tip of the dominant apical bud, and HTLC was measured at the lowest living branch.

2.4. Experimental Design and Data Analysis

We used a mixed-effects analysis of variance (ANOVA) to model (cumulative 11-year) mean height growth (HT), diameter growth (DBH), and height-to-live crown (HTLC) in a split-plot design. The results of initial analyses indicated a strong species effect, which compelled us to run species-specific models for all response variables. Site preparation treatment was considered the whole plot factor, while pre-emergent competition control treatment was considered the split plot factor. The full model in all analyses initially contained block, mechanical site preparation treatment, pre-emergent competition control, and the interaction between mechanical site preparation and pre-emergent competition control as fixed effects. Block was not a factor of interest, but was included in the model as a fixed effect due to low replication (n = 3) [29]. Initial model runs producing an interaction term greater than the suggested threshold ($p > 0.25$ [30]) were pooled and the model rerun with only main effects. To account for nesting, pre-emergent competition control nested within the main mechanical site preparation plot was considered a random effect. A Kenward-Roger approximation was used to estimate the denominator degrees of freedom. Fixed effects were evaluated for significance at $\alpha = 0.05$. Significant fixed effects were further evaluated with LSmeans. Model assumptions of normality and equal variance were confirmed by examining quantile-quantile plots and plots of the residuals. All analyses were conducted in SAS PROC Glimmix (Version 9.4, Cary, NC, USA).

3. Results and Discussion

3.1. Diameter by Mechanical Site Preparation Treatment

The analysis did not detect statistical differences among mechanical treatments for DBH growth for Nuttall oak (p = 0.4206, F = 1.09) or swamp chestnut oak (p = 0.0794, F = 3.74), but differences were observed for Shumard oak (p = 0.0137, F = 4.76). Differences in Nuttall oak and swamp chestnut oak tree DBH were not detected and ranged between 14.49 and 17.20 cm and 11.40 and 13.30 cm, respectively (Table 1).

Table 1. Analysis of diameter of oak trees by species and mechanical site preparation treatment at 11 years post-planting.

	DBH (cm)		
Mechanical Treatment	**Nuttall Oak**	**Shumard Oak**	**Swamp Chestnut Oak**
Control	14.85a *	10.29b	11.40b
Subsoiling	14.49a	9.68b	12.05ab
Bedding	17.20a	11.75a	13.30a
Combination Plowing	15.90a	10.28b	13.08a

* Values within a column followed by the same letter are not significantly different at $\alpha = 0.05$.

While treatment effect differences diminished over the 11-year duration of this study and analysis did not detect significant differences among treatments for Nuttall oak and swamp chestnut oak, it does not necessarily mean that those effects disappeared, but that they were not detected. Variation increases in biological studies over time, thus lessening the power of an analysis while potentially masking continued treatment effects [31,32]. It is likely that separation may occur in a test with more statistical power, but mechanical treatment averages for swamp chestnut oak DBH were not significantly different. However, in Shumard oak, statistically greater DBH growth was observed in trees planted in bedded plots compared with those planted in control, subsoiling, or combination plowing areas (11.75, 10.29, 9.68, and 10.28 cm, respectively).

Researchers studying various methods of mechanical site preparation have often reported differences in their effects on oak growth in younger plantations [3,18,20,33]. Subsoiling has been observed to increase early seedling height growth and/or survival in studies comparing its benefits to oak seedlings [3,10,12,13,18]. However, the lack of differentiation among seedlings grown in subsoiled and unsubsoiled plots was noted in earlier studies that involved the seedlings reported in this paper [4,20]. The authors deduced that the absence of detected differences in seedlings grown in subsoiled compared with control plots was a function of good growing season weather conditions, proper planting technique and vegetative control, as well as the soil quality of the growing site. The authors also indicated that soil compaction was lessened by all three mechanical treatments, and predicted that trees in subsoiled treatment areas would statistically separate from those in control areas in the future. Interestingly, this separation had not occurred by the eleventh growing season and is unlikely to in the foreseeable future, as intraspecific competition is expected to increase with further crown and root development.

Greater diameter growth of oaks planted in bedded plots compared with control or subsoil plots was observed in earlier reports involving trees planted in this study [4,20]. Conversely, at 11 years, differences in DBH averages for mechanical treatments were not detected in Nuttall oak or swamp chestnut oak; however, Shumard oak exhibited a greater DBH in bedded compared with other treatment areas. The Baker/Broadfoot site evaluation methodology [34] was used to select suitable species at project initiation; however, the study site received some periodic short-term flooding in the first few years of this study. Shumard oak is less tolerant of soil saturation than swamp chestnut oak, which is less tolerant than Nuttall oak [35]. This, combined with greater overall height observed for Shumard oak (Table 2), likely points to differences in inherent capability for growth among species.

Table 2. Analysis of total height of oak trees by species and mechanical site preparation treatment at 11 years post-planting.

	Height (m)		
Mechanical Treatment	**Nuttall Oak**	**Shumard Oak**	**Swamp Chestnut Oak**
Control	11.95a *	12.18a	8.62bc
Subsoiling	10.22a	12.68a	7.80c
Bedding	11.50a	13.57a	9.67a
Combination Plowing	11.10a	13.48a	8.82ab

* Values within a column followed by the same letter are not significantly different at $\alpha = 0.05$.

3.2. Height by Mechanical Site Preparation Treatment

The analysis did not detect significant main effect differences for HT among site preparation treatments for Nuttall oak ($p = 0.3811$, F = 1.22) or Shumard oak ($p = 0.3845$, F = 1.21). Swamp chestnut oak analysis yielded a p-value of 0.0203 (F = 7.24) but treatment means were not significant. Consequently, mechanical treatment differences were not considered significant in swamp chestnut oak. The average HT of Nuttall oak, Shumard oak, and swamp chestnut oak trees ranged between 10.22 and 11.95 m, 12.18 and 13.57 m, and 7.80 and 9.67 m, respectively (Table 2).

Bedding and combination plowing were found to result in greater height compared with control and subsoiling treatments in earlier work involving trees from this study [4,20]. It is likely that improved soil drainage and aeration and incorporation of organic matter into the more intensive site preparation treatments served to enhance these early positive results. While treatment effects seem to have evened over the 11-year duration of this study and analysis did not detect significant differences among them, it does not necessarily mean that those effects have disappeared, just that they were not detected.

Some generalized biological trends seem to be manifesting by age 11. While not analyzed together, swamp chestnut oak is expected to be smaller than Nuttall oak on average [34,35]. The HT of swamp chestnut oak was appreciably less than that of Nuttall oak and Shumard oak. In addition, while not as fast-growing as Nuttall oak, Shumard oak is known to grow taller than either of the other two species as it matures [35]. This generalization seems to already be present in this study by age 11.

3.3. Height to Live Crown by Mechanical Site Preparation Treatment

The analysis did not detect main effect differences in HTLC among mechanical treatments for Nuttall oak ($p = 0.4338$, F = 0.96) or Shumard oak ($p = 0.6383$, F = 0.58). Swamp chestnut oak possessed a p-value of 0.0369 (F = 3.55), but treatment means were linked due to low statistical power, and mechanical treatment differences were not considered significant in swamp chestnut oak. The HTLC averages for Nuttall oak, Shumard oak, and swamp chestnut oak trees ranged between 3.28 and 3.80 m, 3.75 and 4.05 m, and 2.12 and 2.85 m, respectively (Table 3).

Table 3. Analysis of height to live crown of oak trees by species and mechanical site preparation treatment at 11 years post-planting.

	Height to Live Crown (m)		
Mechanical Treatment	**Nuttall Oak**	**Shumard Oak**	**Swamp Chestnut Oak**
Control	3.55a *	4.02a	2.43ab
Subsoiling	3.51a	3.87a	2.35b
Bedding	3.80a	4.05a	2.85a
Combination Plowing	3.28a	3.75a	2.12b

* Values within a column followed by the same letter are not significantly different at $\alpha = 0.05$.

While HTLC differences were not detected among the treatments in this study, some typical biological expectations for the tested species were observed. As previously stated, grown under similar conditions, swamp chestnut oak is typically shorter than Nuttall oak or Shumard oak [35]. The average HT of swamp chestnut oak was substantially less than that of Nuttall oak and Shumard oak (Table 2). Excluding inherent growth differences of different species, if light is not limited, shorter trees typically exhibit crown systems closer to the ground [36,37]. This was substantiated by the notably lower HTLC observed for swamp chestnut oak (Table 3).

Another interesting trend that seems to be developing is that of low HTLC in Nuttall oak. Nuttall oak is known to possess poor self-pruning characteristics [35]. This is important to note considering the substantially greater DBH averages of Nuttall oak compared with those of Shumard oak in this study. Knowledge of this trend is of value to managers of Nuttall-oak-dominant plantations across the LMAV. Poor pruning and low HTLC are very likely to negatively impact the future commercial value of these stands as they mature through the creation of a larger, knottier, inner core than that of naturally regenerated trees.

4. Conclusions

Establishment of hardwood plantations in the LMAV has resulted in a stand type that was relatively unknown to forest managers prior to a few decades ago. Commercial management of hardwood stands occurred in naturally regenerated systems that do not typically develop under the low-density, single-species conditions typical of hardwood plantations. The initial efforts in these systems centered on the development of appropriate establishment techniques to ensure the survival and future growth of planted seedlings. The next stage of learning how to manage these stands involves qualifying and quantifying how they develop as they mature. In order to formulate management procedures for how to maximize end-of-rotation stem quality, further studies of the treatment effects on growth, survival, and bole quality are needed.

Most LMAV plantation establishment has occurred on retired agricultural fields, which often possess soil-related problems due to past land use [7]. Mechanical treatment of these soils is often prescribed to correct some of these issues. While site preparation of these soils is often reported to affect survival in plantations, proper planting techniques utilizing high-quality seedlings and good environmental conditions likely resulted in the excellent survival observed in this study.

An earlier paper published in this journal [20], involving the stems included in this study reported differences among mechanical site preparation treatments for all three oak species with seedlings grown in bedding and combination plowing treatments exhibiting greater diameter and height than those grown in control or subsoiling plots. While treatment differences may still exist, they are mostly undetectable at 11 years, indicating an "evening out" of treatment effects over time. As such, the results of this study suggest that, given good site conditions and adequate initial vegetative control, the importance of properly planting good quality seedlings likely outweighs the impact of mechanical site preparation. This does not negate the potential benefit of mechanical site preparation in regard to improved seedling performance on unfavorable sites or during drought conditions, but may mean that the primary use of mechanical treatments is simply to ensure early survival on those sites.

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