The survival and growth of shortleaf pine systems in the Missouri Ozarks: Effects of competition, genetics, and site preparation

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The undersigned, appointed by the Dean of the Graduate School, have examined the thesis entitled

THE SURVIVAL AND GROWTH OF SHORTLEAF PINE SYSTEMS IN THE MISSOURI OZARKS: EFFECTS OF COMPETITION, GENETICS, AND SITE PREPARATION

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Abstract

Establishing shortleaf pine (*Pinus echinata*) across portions of its historical range has proven challenging due to shade intolerance, slow early growth, and poor competitive ability. The objectives of this study were to determine the expected survival and growth rates of planted shortleaf pine relative to artificial and natural hardwoods, identify barriers to regeneration success, and develop tools for individual tree assessment. Data from three long-term studies in southeastern Missouri were used to examine the survival and growth of over 5500, 1-0 seedlings as a function of understory competition, overstory density, genetic selection, and site preparation in artificially and naturally regenerated stands. Growth of planted 1-0 shortleaf pine exceeded that of planted 1-0 white oak (*Quercus alba)* and northern red oak (*Q. rubra*) when grown in the open during a 22-year monitoring period. However, during the first 10 years, planted shortleaf pine had lower survival and height growth where competing with natural oaks and other hardwood regeneration originating from advance reproduction rather than planted seedlings. Regression analysis indicated that height and diameter growth in natural stands was further reduced by retaining a hardwood overstory, while survival was not. Planted shortleaf pine grows faster than planted oaks in open stands with few other hardwood competitors. However, most regeneration occurs in mixed hardwood stands where large advance reproduction outcompetes planted shortleaf pine after harvesting. Due to the variation encountered in shortleaf pine growth, height-growth percentiles present an opportunity to assess and classify individual trees, while allowing for predictions to be made about future growth potential.

Chapter 1:

Introduction and Literature Review

Shortleaf pine silvics

Shortleaf pine (*Pinus echinata*) has the widest distribution of any southern yellow pine in the United States. Its range includes portions of 22 states from New York and New Jersey in the northeast to Texas and Oklahoma in the south-central part of the country, an area encompassing over 1.1 million km^2 (440,000 mi^2) (Lawson 1990). Despite this broad range, it is estimated that fully half the volume of shortleaf pine is located west of the Mississippi River (Murphy and Beltz 1981). Shortleaf pine is the only pine species native to Missouri, where it once covered over 2.5 million hectares in the southern part of the state (Mattoon 1915, Liming 1946). Shortleaf pine could historically be found growing among a number of hardwood and conifer species, including oaks (*Quercus* spp.), hickories (*Carya* spp.), and other, mainly upland, hardwood species, as well as loblolly (*Pinus taeda*) and Virginia (*P. virginiana*) pines (Mattoon 1915, Lawson 1987, Lawson 1990, Cunningham 2007, Guldin 2007). Shortleaf pine is a major component of several associated forest types based on the proportion of stocking and as adopted by the Society of American Foresters: Shortleaf Pine (Type 75), Shortleaf Pine-Oak (Type 76), and Loblolly-Shortleaf Pine (Type 80) (Eyre 1980). In addition, it occurs as a minor component in multiple other forest types throughout its range, including: Eastern White Pine (Type 21), Post-Blackjack Oak (Type 40), White-Black-Northern Red Oak (Type 52), Loblolly Pine-Hardwood (Type 82), Eastern Redcedar (Type 46), and at least ten other identified forest types (Eyre 1980, Lawson 1990).

With a wide distribution and many common species associations, it is not surprising that shortleaf pine is adapted to a diverse range of environmental gradients, encompassing everything from edaphic factors to climate variations. Shortleaf pine can tolerate a variety of soil conditions including texture, depth, nutrient composition, and parent materials, though the most favorable growth characteristics occur on deep, well-drained soils of silty or sandy loams in the Ultisols series (Guldin 1987, Lawson 1990). In Missouri, shortleaf pine occurs in Ultisols and Alfisols. Shortleaf pine, and the common associates of upland oaks, tend to dominate nutrient-poor and excessively drained soils throughout their respective ranges and seem to be particularly adapted to stands having low site quality (Brinkman and Rogers 1967, Cain and Shelton 2000, Kabrick et al. 2015).

Climatically, the shortleaf pine range contains major extremes in both temperature and moisture. Precipitation varies between 1020 mm (approximately 40 inches) toward the southwestern extreme of the range, to over 1500 mm (60 inches) in the south and eastern edges of its botanical range (Guldin 1987). Shortleaf pine can also be found across an elevation gradient, ranging from a low of approximately 3 m (10 feet) in the northeast Atlantic states, to over 900 m (approximately 3,000 feet) in the Appalachian Mountains, where up to 40 cm of snowfall may occur (Lawson 1990). Annual temperature averages and extremes are also dependent upon latitude and elevation. In New Jersey, the northeastern most extent of its range, mean annual temperature is approximately 8.9°C (48°F), in Arkansas, the mean annual temperature is 15.6°C (60°F), while the extreme southwest edge of the range has a mean annual temperature of 28.9°C (84°F). This gradient therefore results in a variation of growing season length from a minimum of approximately 5 months in New Jersey, to over 8 months in Louisiana, Texas, and Oklahoma (Mattoon 1915).

Shortleaf pine history in Missouri

In Missouri, shortleaf pines were once a significant component of Ozark forests, prized for their superior timber properties and abundance on the landscape (Parker 1867, Mohr 1897, Liming 1946). Following the end of the Civil War in 1865, the demography of the country changed significantly (Switzler 1881). The population began to grow and expand westward. The opening of the American West created a strong demand for timber that could not be satisfied by the depleted forests of the eastern United States (Fernow 1899). As a result, interest in the forested Ozarks as a wood source increased (Parker 1867). Land prospectors and timber processors purchased the timber land, and the decades-long cutting of the Ozarks began shortly thereafter (Hill 1949). Large-scale deforestation that ran unabated through the end of the First World War led to a substantial decline in shortleaf pine numbers throughout the state, triggering a succession to forests dominated by hardwoods (Cunningham 2007).

Problem identification

Despite a decline in numbers and economic importance through time, shortleaf pine was regarded as a superior timber tree; it was easily regenerated, possessed a rapid growth rate that allowed it to reach merchantable sizes quickly, and exhibited remarkable wood quality characteristics (Mohr 1897, Mattoon 1915, Liming 1946). By the mid-20th century and beyond, the perception of shortleaf pine began to change in the literature; there was evidence suggesting that there were regeneration difficulties, complications related to slow growth, and low competitive ability. These complications, especially with natural regeneration, establishment and early growth, were attributed to the compounding effects of repeated fires, obstruction of the seedbed by leaf litter and logging slash, and the lack of seed trees (Liming 1946, Brinkman and Smith 1968). The removal of the shortleaf pine component from mixed hardwood-pine stands led to much of the difficulty recently encountered in restoration—namely the lack of a mechanism for natural regeneration (Guldin 2007).

Regeneration efforts

A reduced or absent seed source has prompted land managers and restoration practitioners to rely upon artificial regeneration (planting of seedling stock) as the primary method to establish shortleaf pine in Missouri (Jensen et al. 2007). Stands more recently dominated by shortleaf pine are less likely to exhibit natural regeneration complications, as existing seed trees are typically able to sustain reproduction (Lawson 1987). Though artificial regeneration tends to be associated with improved survivability and growth (Gwaze et al. 2006), high mortality, slow growth, and risk of suppression by woody competition continue to plague restoration efforts throughout Missouri (Barnett et al. 1987, Lawson 1990, Guldin 2007, Kabrick et al. 2015). Though shortleaf pine is currently not considered to have high commercial value, its restoration is a priority throughout Missouri to increase wildlife diversity, herbaceous and woody species diversity, and forest resilience (Eddleman et al. 2007, Masters 2007, Kabrick et al. 2015, Kabrick et al 2017). Artificial and natural regeneration methods have led to mixed success due to fire suppression, understory competition, lack of seedling establishment, and slow seedling growth (Lawson 1990, Gwaze et al. 2006, Jensen et al. 2007, Stambaugh et al. 2007). Similarly, the challenges facing shortleaf pine restoration efforts can include competition from woody and herbaceous vegetation in the understory, lack of genetic diversity, and altered disturbance regimes (Dougherty and Lowery 1987, Lowery 1987, Lawson 1990, Gwaze et al. 2007, Broadhurst et al. 2008). Therefore, there is a need to identify methods for increasing the early survival and growth of shortleaf pine seedlings.

Barriers to restoration

Several factors can influence the ability of shortleaf pine to successfully establish and grow on a given site. The history of recurrent tree harvesting operations common throughout much of the timbered lands in the United States can remove significant amounts of biomass from a forested site and cause compaction of forest soils. Biomass removals have not been shown to reduce stand volume in the international Long-Term Soil Productivity study (Ponder et al. 2012). The lack of long-term decreases in productivity associated with site biomass removal suggests that excessive nutrient removals associated with practices such as biomass harvesting will have few measurable effects when conducted only one time. However, reductions in survival or growth due to nutrient losses associated with biomass harvesting may not be realized for several rotations. In contrast, soil compaction has been shown to lead to changes to the physical, chemical, and biological properties of the soil. Compaction can change the distribution of soil pores, decrease overall porosity, reduce water infiltration and percolation, inhibit root growth, minimize aeration, and adversely affect nutrient uptake and cycling (Grable and Siemer 1968, Archer and Smith 1972, Ponder 2004). Forest soil compaction has been shown to negatively affect both tree growth and survival (Froehlich and McNabb 1984, Froehlich 1988, Powers et al. 1990). Although compaction is typically associated with reduced tree growth, it has been shown to increase overall tree survival and growth in studies of mixed hardwood-conifer forests (Powers et al. 2005, Ponder et al. 2012). Other studies by Brais (2001) and Gomez et al. (2002) found compaction to increase growth of several conifer species: ponderosa pine (*Pinus ponderosa)*, jack pine (*P. banksiana)*, and black spruce (*Picea mariana)*. A long-term study of shortleaf pine in Missouri similarly found significant height growth increases following soil compaction (Ponder 2004, Ponder 2007, Ponder et al. 2012). Though there are apparent short-term benefits to conifer growth under certain soil conditions, compacted forest soils typically require several decades to recover a non-compacted bulk density (Sands et al. 1979). Soil recovery can be affected by several factors, namely repeated exposure to compacting events from tree and/or biomass harvesting, soil moisture variations, coarse fragment content, and cryoturbation (Liechty et al. 2002).

Shortleaf pine regeneration and yields

When regenerating stands containing shortleaf pine, there is an operational need at an early stand age to distinguish between trees that are likely to become canopy dominant or codominant trees from those that will not. Site index curves (e.g. Nash 1963) provide meaningful insight into the expected heights of dominant or codominant trees for a given site quality but only apply to stands where trees are at least 10 years old or older (Carmean et al. 1989, Lawson 1990). Where shortleaf pine seedlings are naturally or artificially regenerated, the presence of woody and herbaceous competition can severely limit their growth and survival potential, thereby reducing the probability of regeneration success, adversely impacting the efficacy of growth and yield tables, site index curves, and species growth curves (Guldin 2007, Dougherty and Lowery 1987, Lowery 1987, Sander and Rogers 1979, Lowery). Though complex interactions in the early stages of stand development can cause differential growth patterns, many species can exhibit height differentiation before other growth metrics become viable, and early growth can be a strong indicator of future performance (Oliver and Larson 1996, Assmann 1970). Despite these strong correlations between early growth and survival, there is a paucity of information available about how to best obtain optimal regeneration success in shortleaf pine systems. Considerable research into site preparation methods, spacing, herbicide use, and genetics exist for the improvement of other southern yellow pine species, including loblolly (*Pinus taeda*), slash (*P. elliotti*), and longleaf (*P. palustris*) pines (Lewis et al. 1985, Baldwin, Jr. et al. 2000, Raley et al. 2003, Land, Jr. et al. 2004, Schubert et al. 2004, South et al. 2004). Studies involving plantation development, spacing manipulations, and silvopasture creation are also common for these species throughout the southern pine region, though the concentration of research trends toward the improvement of loblolly pine (Lewis et al. 1985, Clason and Robinson 2000, Adams and Clason 2002, Land Jr. et al. 2004, Schubert et al. 2004, Fox et al. 2007). There is markedly less current or salient research into these same practices to increase the survival and growth of shortleaf pine, which would be beneficial to informing upon the regeneration and restoration of this species throughout its range.

Shortleaf pine genetic improvement

Employing genetics to improve shortleaf pine throughout the United States for reforestation began in 1959 (Kitchens 1987). In the early 1960s, tree improvement efforts began in the Ouachita and Ozark National Forests in Arkansas and Oklahoma. Trees were selected in the forests based on growth and form, perceived insect and disease resistance, flowering/reproduction characteristics, wood specific gravity, and location (see FSH 2409.26g Tree Improvement Handbook Region 8, Amendment 94-1). Several years after the selection of trees in Region 8, foresters on the Mark Twain National Forest (Region 9) performed an assessment of superior shortleaf pine specimens in Missouri (Studyvin and Gwaze 2007, Gwaze et al. 2005). Scions of selected trees were collected and grafted onto root stock at the previously established seed orchard located at the Ouachita National Forest near Mount Ida, Arkansas between 1969 and 1971 (Gwaze et al. 2005). The decision to deploy the first-generation genetic test in Arkansas, rather than Missouri, was based in part on financial considerations (it would be less expensive to utilize the already operational seed orchard in Arkansas than to establish one in Missouri), and part on the expectation that Missouri shortleaf pines grown in a more southerly location would reduce flowering age and increase cone production (Studyvin and Gwaze 2007). The seed orchard at Mount Ida was intensively managed. A 122-m (400 foot) buffer strip surrounded the grafted trees to not only separate geographic sources but to also prevent local pollen sources from mixing with the selected trees and provide a measure of protection from wildfires (Studyvin and Gwaze 2007). In addition, the site was subjected to multiple applications of a wide array of pesticides, mowing, or herbicide (depending on space between trees and/or terrain) to control weeds, and ammonium nitrate fertilizer (34-0-0) to increase growth and cone production (Studyvin and Gwaze 2007). The breeding program for the Missouri material consisted of eight, 6x6 disconnected partial diallel crossing groups based on a single-pair mating design, which resulted in a total of 305 crosses from the 50 selected parents; an additional 200 crosses between both Missouri and Arkansas parents were anticipated, but only several were accomplished (Studyvin and Gwaze 2007, Smith 2011). Starting in the late 1970s and into the early 1980s, first-generation progeny tests were initiated at three separate sites within Missouri, utilizing the material collected from the seed orchard at Mount Ida, Arkansas (Gwaze et al. 2005, Smith 2011). Over 10 evaluation plantations were created from 1980-1983, but severe heat, drought, and pest infestations resulted in complete mortality for all but two series (Gwaze et al. 2005, Studyvin and Gwaze 2007). In 1983, the Missouri Department of Conservation entered into a cooperation agreement with the USDA Forest Service to provide the state with first- and second-generation improved seed supply (Kitchens 1987). The cone harvest in 1986 was extraordinarily large, with over 7 million cones (approximately 11,000 pounds of pine seed) collected by a staff of 100 over a month. The seeds corresponding to the Mark Twain National Forest parents were provided to the Missouri Department of Conservation and stored at the George O. White State Nursey in Licking, MO, where they continue to be used for seedling production to this day (Studyvin and Gwaze 2007, Smith 2011). In 2002, a full-sib progeny test was planted at the White State Nursery with seed material from the Mark Twain National Forest shortleaf pine tree improvement program, as well as material from two other sources: the Ozark National Forest and Shawnee National Forest breeding programs in Arkansas and Illinois, respectively (Studyvin and Gwaze 2007, Smith 2011). The 2002 progeny test was established as a randomized complete-block design with six blocks across two sites at the nursey. After clearing existing vegetation from the site with a bulldozer, seedlings were planted in a 3.05 x 3.05 m spacing. Rows were mowed at least once per year, and herbicides were applied at three and four years after planting (Smith 2011). At age six, height and diameter of seedlings were measured and analyzed to determine the genetic control and heritability of certain growth traits in shortleaf pine (Gwaze et al. 2005, Smith 2011). Of the more than 300 crosses analyzed by Smith (2011), twenty-four families were selected for a second progeny test planting at the Wurdack Research Center in Crawford County, MO in early 2010.

Study purpose

The complications in shortleaf pine reforestation and restoration run counter to the dynamic observed in historical systems where shortleaf pine historically thrived in stands with a high level of biodiversity, and thus requires further investigation to determine the factors preventing the successful restoration of this species, while aiming to identify the variables that would contribute to improved establishment and growth of these important ecosystems. Survival probability, height growth, and diameter growth from shortleaf pine planted under a variety of forest types at three different sites in the Missouri Ozarks will be analyzed to determine what factors contribute to increased restoration success. These data will be used to create a height-growth percentile chart that can be deployed in the field to rapidly assess the current progress and future survival and growth potential of a specific tree for restoration.

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Chapter 2:

Study Sites and Experimental Designs

Long-Term Soil Productivity (LTSP) Program

Site. The LTSP program is located within the Current River Conservation Area (formerly Carr's Creek State Forest) in Shannon County, MO (N 37°10'48", W 91°06'36"*).* The purpose of the LTSP study is to determine the effects of harvest-related disturbances, mainly soil compaction and biomass removal, on the productivity of forests over a range of different ecosystem types across North America (Powers et al. 1990). Soils at the Missouri site consist primarily of the rocky, nutrient-poor Clarksville series (loamy-skeletal, siliceous, semi-active, mesic Typic Paleudults), formed from hillslope sediments and cherty residuum from dolomite (NRCS *Web Soil Survey* 2017). Prior to study initiation, the site was occupied by a mature second-growth oak (*Quercus* spp.)- hickory (*Carya* spp.) forest (Ponder and Mikkelson 1995). Site index at 50 years for shortleaf pine is approximately 18 m (California Soil Resource Lab *SoilWeb* 2017). An on-site Remote Automatic Weather Station (RAWS) collects daily temperature and precipitation measurements. Weather data from February 2001 to November 2018 were analyzed, resulting in a mean annual temperature at the site of 14.0 ^{0}C, and average annual precipitation of 1130 mm during that period (RAWS data, Desert Research Institute).

Experimental design. The LTSP protocol consists of nine treatments in a 3x3 split-plot factorial design, derived from combining three levels of biomass removal and soil compaction. Additionally, each treatment plot is split, with half receiving chemical herbicide to control understory vegetation. The entire site was clearcut prior to the application of treatment effects and seedling planting. Pre-treatment harvesting took place in early 1994. Treatment application and seedling planting occurred in Spring 1995. All seedlings were 1-0 bareroot stock from the George O. White State Nursery in Licking, MO. Seedling counts were 2,380 northern red oak, 2,467 white oak, and 763 shortleaf pine, for a total of 5,610 seedlings. Whole-plot soil compaction was performed at three levels, which included: no compaction (whole-soil density approximately 1.30 g cm^{-3}), moderate compaction (whole-soil density ~ 1.55 g cm^{-3}), and severe compaction (whole-soil density ~ 1.80 g cm^{-3}). Soil compaction was done using a 14-ton vibrating sheep's foot roller, with field measurements of soil bulk density performed after each pass of the roller. Moderate compaction plots received three passes, while severe compaction plots received between five and eight passes. Changes in bulk density were not observed beyond five passes, however (Ponder 1997). At study inception, bulk densities were based upon whole-soil (not fine-earth) fractions. Plots designated for compaction treatments had post-harvest biomass removed and stored prior to application of the compaction treatment, after which, the respective biomass was returned to the plot. Plots that did not receive compaction treatments had harvested biomass removed utilizing a cable yarding system to minimize potential soil disturbance from logging equipment. The three levels of whole-plot biomass removal were sawlog only, where branches, tops and litter remained on-site after harvest; whole-tree, where the entire above-ground biomass was removed; whole-tree plus forest floor, which includes whole-tree removal, plus the raking of forest floor litter down to the mineral soil. For each whole-plot treatment, half of each plot was designated for a vegetation control (VC) treatment utilizing herbicides, while the other half-plot would develop a natural understory. In the section of each plot with no vegetation control, typical hardwoods present included red maple (*Acer rubrum)*, blackgum (*Nyssa sylvatica)*, hickory (*Carya* spp.), and dogwood (*Cornus florida).*

In all plots, a mixture of glyphosate and simazine was applied using a manual backpack and sprayed in a 1m radius around each oak and pine seedling to control understory vegetation. Glyphosate was applied at a rate of 3.0 kg ha^{-1} while the simazine rate was 3.6 kg ha^{-1}. Herbicide was applied in late spring following seedling planting, and again annually through the second growing season. Starting with the third growing season, ½ of each plot was designated as VC, and received an annual herbicide application through ten growing seasons. The understory in vegetation-controlled areas remains remarkably free of herbaceous and woody vegetation, despite the cessation of herbicide applications over a decade ago (personal observation).

Tree measurements. Tree heights and diameter at breast height (basal diameter if tree height <1.4 m) were measured after planting and annually through age 10. Measurements were also taken at ages 19 and 22. The most recent, 22^{nd}-year collection took place in the summer of 2016. Additional data collection points exist between ages 10 and 19 but are incomplete, and therefore not included in the following analyses.

Additional information. The spring of 1995 was extremely dry, resulting in high mortality the first growing season, especially in shortleaf pine (approximately 29% of planted seedlings died). Subsequently, seedlings were watered once in late 1995 (Ponder 1997). Further, extensive rodent damage in the first growing season facilitated the need to place plastic tree shelters around all seedlings (Ponder 1997, Ponder 2007). It is not known how long these shelters remained in place. Severe snow and ice in the winter of 2000-2001 damaged 34 shortleaf pines, 14 in the no compaction treatment, 9 in the moderate, and 12 in severe compaction. Most (33) of the trees were in the vegetation control treatments as well. The biomass removal treatments to which these trees belong were not identified. Following a growing season in which affected trees exhibited abnormal growth characteristics, a decision was made to remove these damaged trees from the study in the summer of 2002 (Ponder 2007).

Sinkin Experimental Forest (Sinkin)

Site. The Sinkin is located within portions of Reynolds and Dent Counties, MO (*N 37°29’24”, W 91°15’36”)*. Soils include the Clarksville and Coulstone series, both loamy-skeletal, siliceous, semi-active, mesic Typic Paleudults, and the Nixa series, a loamy-skeletal, siliceous, active, mesic Glossic Fragiudults (NRCS *Web Soil Survey* 2017).

Experimental design. The treatment included underplanting 1-0 bareroot shortleaf pine seedlings in an existing second-growth mixed hardwood stand after manipulating the overstory density from 0 to 73% stocking. A severe storm one year after seedling planting removed additional overstory trees in some treatment plots, lowering the overstory density and residual basal areas per plot. In this study, the nearest hardwood competitor within 1.37 m to each planted shortleaf pine seedling was identified, tagged, and measured. These hardwood competitors were from either advanced reproduction, or stump sprouts. This distance was selected because it corresponds to the growing space requirement of a 11-cm dbh oak tree as determined with published stocking equations (Gingrich 1967), thus representing the future growing space requirement of dominant and codominant hardwood competitors when the stand reaches age 20. This growing space requirement corresponds to the plot size used for assessing oak advance reproduction adequacy described by Sander et al. (1984).

Tree measurements. The shortleaf pines were planted in 2007 and height and diameter (basal diameter or diameter at breast height, depending on height) were recorded annually from 2008 to 2010, and again in 2013 and 2017. Hardwood competitors were identified, tagged, and measured in 2010, 2013, and 2017.

Wurdack Research Center (Wurdack)

Site. Wurdack is located in Crawford County, MO (*N 37°47'24", W 91°25'12").* The site is a continuous, south-facing slope of 10-30%, with two soil series occurring: Reuter, a loamy-skeletal, siliceous, active, mesic Typic Paleudalfs on the upper and lower backslopes, and Goss, a clayey-skeletal, mixed, active, mesic Typic Paleudalfs occurring on lower slope positions (NRCS *Web Soil Survey* 2017).

Experimental design. Seedlings consisted of genetically improved, 1-0 shortleaf pine stock representing 12 full-sib families, plus standard, orchard-run seedlings from the state nursey at Licking, MO. Families were crossed from elite parents selected in natural stands on the Mark Twain National Forest in the 1970s (Smith 2011, Gwaze et al. 2005). The existing hardwood forest was clearcut, and a masticator was used to grind tree stumps and non-merchantable material. The site was then divided into four blocks. Seedlings were deployed in complete blocks, with 700-1000 seedlings per block. Three blocks had a silvopasture treatment applied, which involved a double row of trees spaced 3.05m x 3.05m followed by a 12.19m wide alley. A mix of native warm and cool season grasses were broadcast seeded into the alleyways. Herbicide pellets (Velpar®) were applied to the seedling planting rows for two years following planting. The fourth block eliminated the alley, leaving rows evenly spaced at 3.05 meters. No herbicides were applied in this block and no grasses were seeded. Instead, an additional 12 families (not replicated in the other three blocks) were selected and planted along with the 12 replicated families.

Tree measurements. Pine height and diameter (basal diameter or diameter at breast height, depending on height) were collected in 2010, 2011, and 2017.

Table 1. Chronology of actions taken for study implementation, treatment, and data collection, by site.

Action	LTSP	Sinkin	Wurdack
Pre-treatment harvest	1994	2007	2009
Study Implementation	1995	2008	2010
Herbicide Application	1995, 1996 (all plots) 1997-2005 (VC treatment only)	N/A	2010, 2011
Data Collection			
Shortleaf height	1995-2005; 2013, 2016	2008-2010; 2013, 2017	2010, 2011, 2017
Hardwood height	1995-2005; 2013, 2016	2010, 2013, 2017	N/A
Shortleaf diameter	1997-2005; 2013, 2016	2008-2010; 2013, 2017	2010, 2011, 2017
Hardwood diameter	1997-2005; 2013, 2016	2010, 2013, 2017	N/A

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Chapter 3:

Effects of biomass removal, soil compaction, and vegetation control on 22nd year tree height growth and survival: Long Term Soil Productivity Study, Missouri

Stephen Lyczak

Abstract

The Long-Term Soil Productivity program is an international study initiated to examine the effects of harvest-related disturbances on site productivity. Sites were subjected to biomass removal, soil compaction, and vegetation control. We analyzed 22nd-year height and survival data from the Missouri installation to determine treatment effects. Soils include the rocky, nutrient-poor Clarksville series: loamy-skeletal, siliceous, semi-active, mesic Typic Paleudults. Bareroot, 1-0 white oak (*Quercus alba*), northern red oak (*Q. rubra*), and shortleaf pine (*Pinus echinata*), were planted at a 3:3:1 ratio. Treatments included three levels of biomass removal (sawlog, whole tree, and whole-tree plus forest floor) and three levels of soil compaction including none (bulk density = 1.30 g cm^{-3}), moderate (bulk density = 1.55 g cm^{-3}), and severe (bulk density = 1.80 g cm^{-3}). Within treatments, vegetation was controlled with herbicide in half of each plot. Vegetation control was significant for height on all species. Average height for red oaks with vegetation control treatments was 884 cm with vs. 606 cm without; white oak was 837 cm with vs. 424 cm without; shortleaf pine was 1339 cm with vs. 1220 cm without. Moderate compaction increased average white oak height by 15% and severe compaction increased average height by 18% compared to no-compaction treatments. Compaction was not significant for red oaks or for shortleaf pines. Whole-tree removal reduced average shortleaf pine heights by 6% vs. sawlog-only removal, while whole-tree+ forest floor removal increased heights 3%. Biomass removal was not significant for either oak species. Red oak survival probability was 0.79 with vegetation control vs. 0.34 without; white oak was 0.81 with vs. 0.65 without;

shortleaf pine was 0.49 with vs. 0.45 without. Overall, vegetation control was the dominant factor driving survival and growth of oaks, and to a lesser degree, growth of shortleaf pine. Biomass removal and compaction treatments had relatively little negative effect on height, indicating the resilience of these species to harvest-related disturbances in Ozark Highlands soils.

Introduction

The long-standing concern about the effects of forest management on sustained forest productivity led to the development of the Long-Term Soil Productivity (LTSP) program. The LTSP program is a world-wide network of study sites established to identify and assess the effects of harvest-related disturbance on long-term soil productivity. Treatments include the removal of organic matter (biomass) from the site and soil compaction (Powers et al. 1990). Understory vegetation control was also considered as competition affects both tree height growth and survival (Wagner et al. 2006, Ponder et al. 2012), potentially interacting with the organic matter removal and compaction treatments. The effects of nutrient and water supply along with competition for these resources can vary by species. Consequently, the LTSP study was designed to test for species differences where study sites included mixed species stands.

Tree harvesting operations can remove significant amounts of biomass from a forested site. With increased efficiency and widespread use of forest products such as pulp, biofuel pellets, and laminated products, the sawlog is no longer the only merchantable component of a tree. Consequently, larger quantities of plant material and nutrients can be removed for use as other forest products. Compaction is also a significant concern, as it can influence the physical, chemical, and biological properties of the soil. Compaction can change the distribution of soil pores, decrease overall porosity, reduce water infiltration and percolation, inhibit root growth, minimize aeration, and adversely affect nutrient uptake and cycling (Grable and Siemer 1968, Archer and Smith 1972, Ponder 2004). Forest soil compaction has been shown to negatively affect both tree growth and survival (Froehlich and McNabb 1984, Froehlich 1988, Powers et al. 1990). Although compaction is typically associated with reduced tree growth, it has been shown to increase overall tree survival and growth across several LTSP installations (Powers et al. 2005, Ponder et al. 2012). Other studies by Brais (2001) and Gomez et al. (2002) found compaction to increase growth of several conifer species: ponderosa pine (*Pinus ponderosa)*, jack pine (*P. banksiana)*, and black spruce (*Picea mariana)*.

The LTSP study includes more than 100 sites across a wide range of forest and landscape types, facilitating analyses of the long-term treatment effects on many different tree species and soils (Powers et al. 1990, Powers and Van Cleve 1991). Each installation incorporates native tree species of high commercial or ecological importance. In Missouri, northern red oak (*Quercus rubra*), white oak (*Q. alba)*, and shortleaf pine (*Pinus echinata)* were used to replicate an oak-pine forest comprised of mixtures of upland oaks and shortleaf pine.

Five- and ten-year results for this study site and for all LTSP study sites have been reported elsewhere (Fleming et al. 2006, Ponder et al. 2012). In this paper, we report on the 22-year effects of the three levels of biomass removal, three levels of soil compaction, and two levels of vegetation control on the survival and growth of northern red oak, white oak, and shortleaf pine.

Methods

Site Description

The study is a part of the USDA Forest Service's Long-Term Soil Productivity (LTSP) program, with this site located in the Current River Conservation Area of Shannon County, MO (N 37°10'48", W 91°06'36"*).* The purpose of the LTSP study is to determine the effects of harvest-related disturbances, mainly soil compaction and biomass removal, on the productivity of forests over a range of different ecosystem types across North America (Powers et al. 1990). Soils at the Missouri site consist primarily of the rocky, nutrient-poor Clarksville series (loamy-skeletal, siliceous, semi-active, mesic Typic Paleudults), formed from hillslope sediments and cherty residuum from dolomite (NRCS *Web Soil Survey* 2017). Prior to study initiation, the site was occupied by a mature second-growth oak (*Quercus* spp.)- hickory (*Carya* spp.) forest (Ponder and Mikkelson 1995). Site index at 50 years for shortleaf pine is approximately 18 m (NRCS *Web Soil Survey* 2017). An on-site Remote Automatic Weather Station (RAWS) collects daily temperature and precipitation measurements. Weather data from February 2001 to November 2018 were analyzed, resulting in a mean annual temperature at the site of 14.0 ^{0}C, and average annual precipitation of 1130 mm during that period (RAWS data, Desert Research Institute 2018).

Experimental Design

The LTSP protocol consists of nine treatments in a 3x3 split-plot factorial design, derived from combining three levels of biomass removal and soil compaction. Additionally, each treatment plot is split, with half receiving chemical herbicide to control understory vegetation. Whole-plot soil compaction was performed at three levels, which included: no compaction (bulk density approximately 1.30 g cm^{-3}), moderate compaction (bulk density ~ 1.55 g cm^{-3}), and severe compaction (bulk density ~ 1.80 g cm^{-3}). Soil compaction was done using a 14-ton vibrating sheep's foot roller, with field measurements of soil bulk density performed after each pass of the roller. Moderate compaction plots received three passes, while severe compaction plots received between five and eight passes. Changes in bulk density were not observed beyond five passes (Ponder 1997). At study inception, bulk densities were based upon whole-soil (not fine-earth) fractions. Plots designated for compaction treatments had post-harvest biomass removed and stored prior to application of the compaction treatment, after which the respective biomass was returned to the plot. Plots that did not receive compaction treatments had harvested biomass removed utilizing a cable yarding system to minimize potential soil disturbance from logging equipment. The three levels of whole-plot biomass removal were sawlog only, where branches, tops and litter remained on-site after harvest; whole-tree, where the entire above-ground biomass was removed; whole-tree plus forest floor, which includes whole-tree removal, plus the raking of forest floor litter down to the mineral soil. For each whole-plot treatment, half of each plot was designated for a vegetation control (VC) treatment utilizing herbicides, while the other half-plot would develop a natural understory. In the section of each plot with no vegetation control, typical hardwoods present included red maple (*Acer rubrum)*, blackgum (*Nyssa sylvatica)*, hickory (*Carya* spp.), and dogwood (*Cornus florida).*

In areas designed VC, a glyphosate-simazine mixture was sprayed in a 1m radius around each seedling to control understory vegetation. Herbicide was applied at seedling planting and again annually through the third growing season. A 1m-radius around all seedlings, regardless of treatment, were sprayed with the same herbicide mixture for 2 growing seasons. The understory in vegetation-controlled areas remains remarkably free of herbaceous and woody vegetation, despite the cessation of herbicide applications over a decade ago (personal observation).

For a complete description of the site characteristics and experimental design, see Ponder and Mikkelson (1995). Pre-treatment harvesting took place in early 1994. Treatment application and seedling planting occurred in Spring 1995. All seedlings were 1-0 bareroot stock from the George O. White State Nursery in Licking, MO. Seedling counts were 2,380 northern red oak, 2,467 white oak, and 763 shortleaf pine, for a total of 5,610 seedlings. The spring of 1995 was extremely dry, resulting in high mortality the first growing season, especially in shortleaf pine (approximately 29% of planted seedlings died). Subsequently, seedlings were watered once in late 1995 (Ponder 1997). Further, extensive rodent damage in the first growing season facilitated the need to place plastic tree shelters around each seedling (Ponder 1997). It is not known how long these shelters remained in place.

Tree measurements

Tree heights were measured after planting, and annually through age 10. Measurements were also taken at ages 19 and 22. The most recent, 22nd-year collection took place in the summer of 2016. Additional data collection points exist between ages 10 and 19 but are incomplete, and therefore not included in these analyses.

Data analyses

Survival probabilities for each species in relation to soil compaction, biomass removal, and vegetation control were determined using logistic regression for the 22nd-year data collection. We used a generalized linear mixed model with a binary distribution (survival =1, mortality =0), logit link function, and random intercept using PROC GLIMMIX in SAS 9.4 software (SAS Institute, Inc., Cary, NC). To minimize the potential effects of pseudo-replication, mean survival probability by treatment was determined through SAS output, while standard error of the mean (SEM) and p-values were calculated separately based on degrees of freedom specific to each treatment. For example, SAS output would calculate the SEM and corresponding p-values using the total sample size (*n*) as the denominator degrees of freedom, reducing the SEM and increasing the p-value. Therefore, we calculated based on the denominator degrees of freedom for each individual treatment, lowering the *n*, which resulted in larger (albeit, accurate) SEM values, and smaller p-values. Given the unbalanced nature of these data, we surmised this method represented the best available analytical approach.

Treatment effects on tree heights were analyzed using a generalized linear mixed model with a Gaussian distribution, identity link function, and random intercept, using PROC GLIMMIX in SAS 9.4 software (SAS Institute, Inc., Cary, NC). We used linear regression to identify relationships between tree height at age 22 and the main effects of soil compaction, biomass removal, and vegetation control, as well as the corresponding interactions between those effects. Least-square means of tree heights were subjected to pairwise comparisons using T-grouping at *alpha*=0.05.

Results

Survival

Twenty-one years after planting, northern red oak survival was significantly affected by vegetation control (p<0.001), with survival probability more than doubling from 34% to 79% when the understory was absent, and by compaction (p= 0.002), where moderate compaction increased survival probability by 13% over non-compacted (Figure 1). Also significant were the interactions of compaction x VC (p= 0.046) and biomass removal x compaction (p= 0.004) (Figure 2). Biomass removal alone was not significant (p=0.297), nor were the interactions of biomass removal x VC (p=0.424) and overall treatment, i.e. biomass removal x compaction x VC (p=0.307) (Not graphically presented).

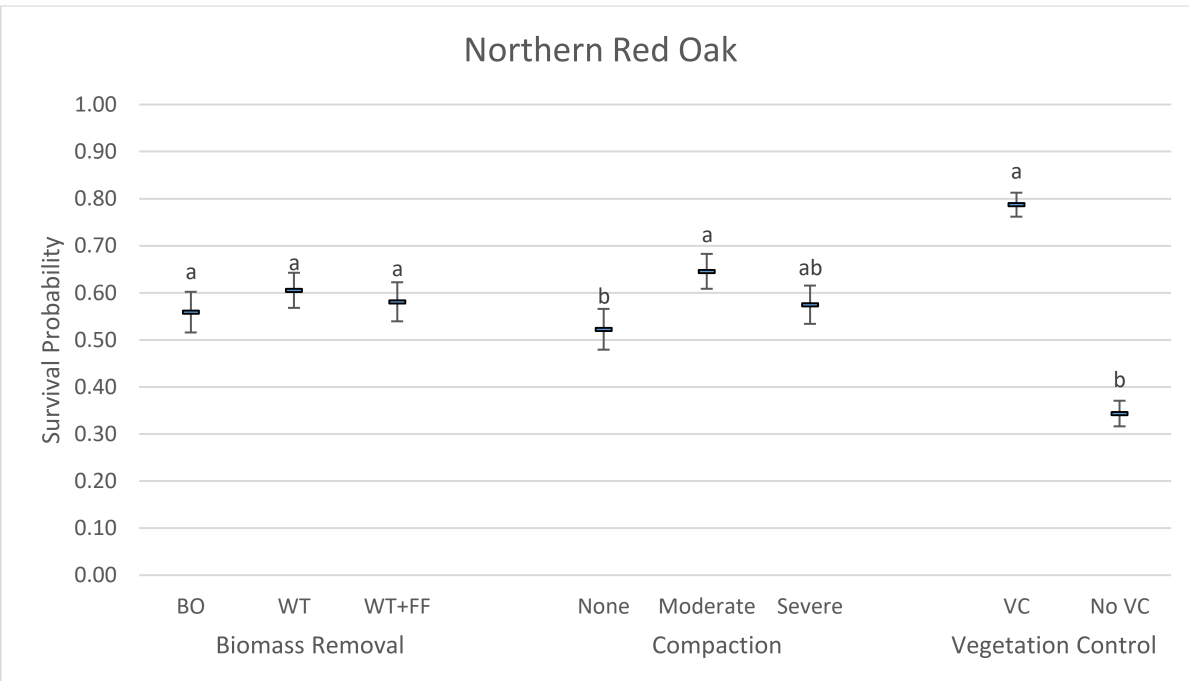

Figure 1. Northern red oak 22nd year survival probabilities by treatment main effects. For biomass removal: BO = bole-only, WT= whole tree, WT+FF= whole tree + forest floor/ leaf litter. Compaction represents none, moderate, and severe as described in "Methods." Vegetation Control indicates whether herbicide was applied (VC) or not applied (No VC). Error bars represent +/- SEM. Within treatments, probabilities that share a letter are not significantly different. Moderate compaction and vegetation control (VC) significantly increased survival probability. Severe compaction insignificantly increased survival probability. Survival probability in non-vegetation controlled (No VC) split-plots was significantly reduced. Biomass removal did not significantly impact survival probability positively or negatively.

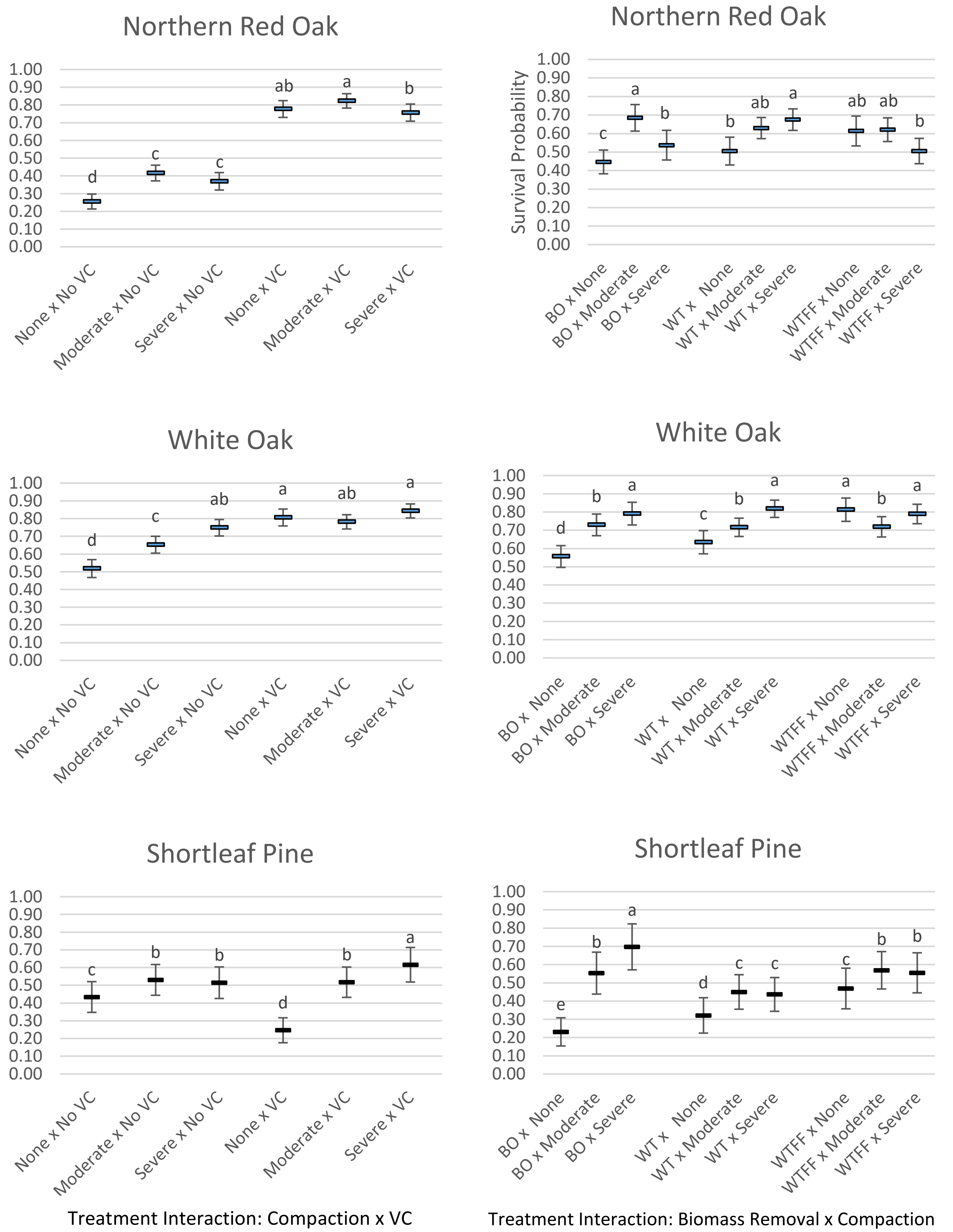

Figure 2. Twenty-second year survival probabilities for northern red oak, white oak, and shortleaf pine by treatment interactions. For each species, graphs on the left present the interaction of compaction x vegetation control (VC); graphs on the right are the interaction of biomass removal x compaction. Within treatments, values which share a letter are not significantly different. Error bars represent +/- standard error of the mean. For biomass removal: BO= bole only (sawlog), WT= whole tree, WT+FF= whole tree + forest floor/leaf litter. Compaction represents none, moderate, or severe as described in "Methods." Vegetation control indicated whether herbicide was applied (VC) or not applied (No VC).

White oak survival after 22 years was significantly impacted by all main effects. Vegetation control increased survival probabilities by 16% (p <0.001), while severe compaction increased survival probability by 12% (p <0.001). Biomass removal was marginally significant (p= 0.022), with increasing levels of removal increasing survival probability (Figure 3). Two interactions were significant. In compaction x VC, compaction increased survival significantly in No VC treatments, with severe compaction probabilities equal to those of the VC treatment (p= 0.010) (Figure 2). For biomass removal x compaction, compaction significantly increased survival probability in sawlog and whole-tree biomass removals but had a mixed effect in whole-tree + forest floor removals (p=0.004) (Figure 2). Interactions between biomass removal x VC, as well as overall treatment effect were not significant (p= 0.180 and p=0.608, respectively).

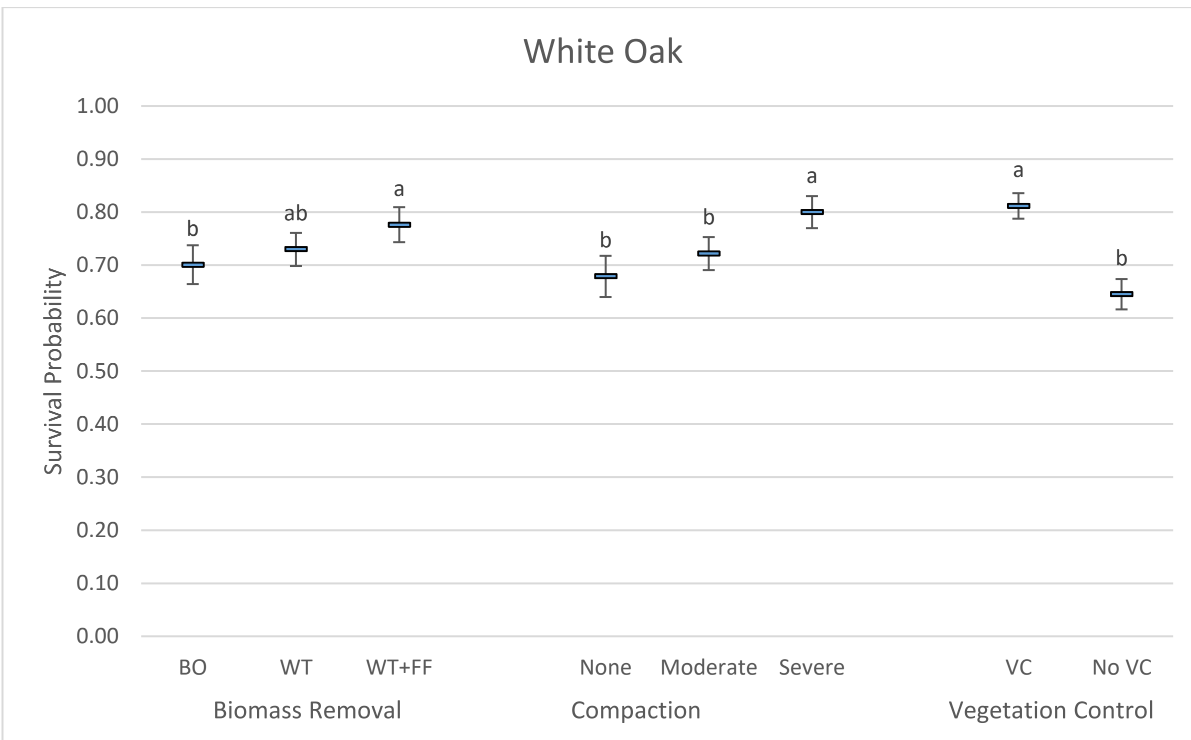

Figure 3. White oak 22nd year survival probabilities by treatment main effects. For biomass removal: BO = bole-only, WT= whole tree, WT+FF= whole tree + forest floor/ leaf litter. Compaction represents none, moderate, and severe as described in "Methods." Vegetation Control indicates whether herbicide was applied (VC) or not applied (No VC). Error bars represent +/- SEM. Within treatments, probabilities that share a letter are not significantly different. Biomass removal, compaction, and VC significantly increased survival probability.

Shortleaf pine 22nd year survival probability was not significantly affected by VC (p=0.294) but was significantly increased by compaction (p<0.001), while biomass removal had a significant, though not linear, effect (p=.013) (Figure 4). The biomass x compaction interaction was significant (p=0.009) where compaction increased survival when only the sawlog was removed but had a mixed effect with other biomass removals (Figure 2). The compaction interaction with VC was also significant (p=.006). Where compaction treatments were not applied, no VC had nearly doubled survival probability vs VC, while in severely compacted plots, VC survival probability was 10% higher than no-VC (Figure 2).

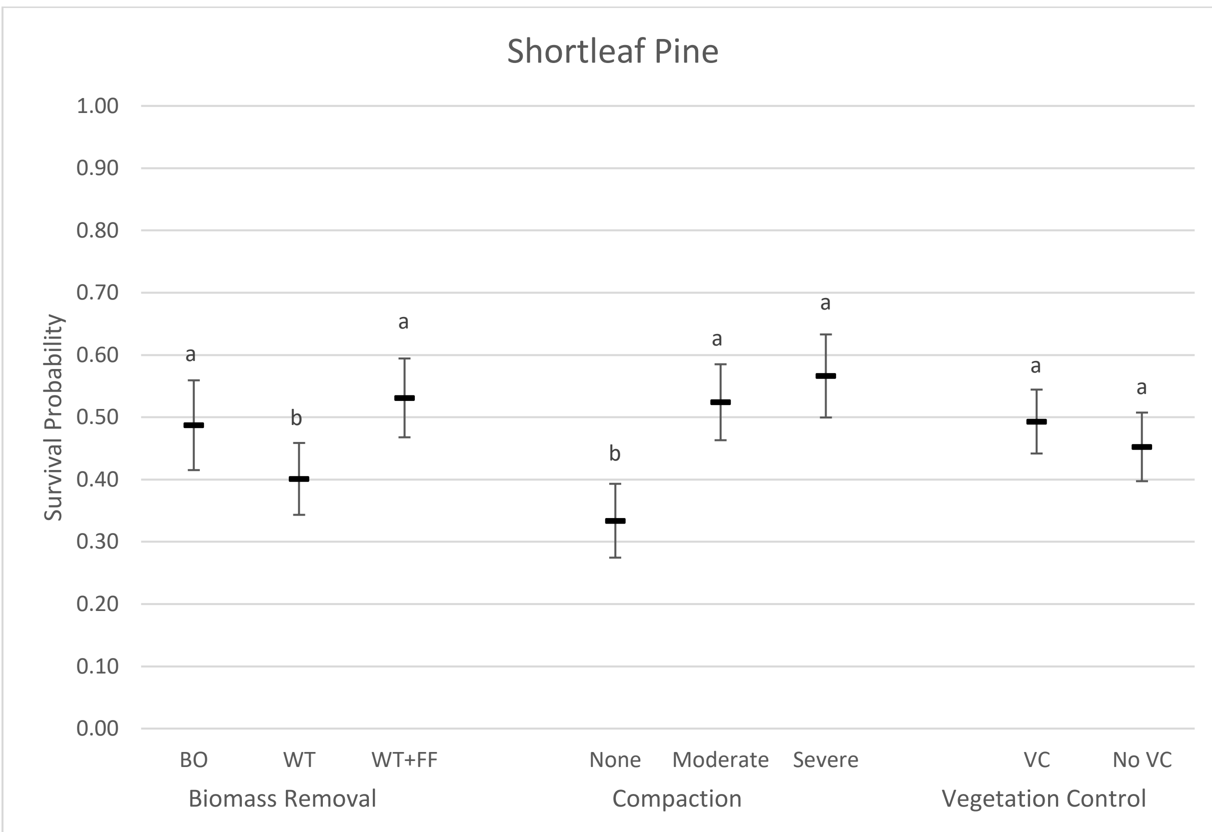

Figure 4. Shortleaf pine oak survival probabilities by treatment main effects. For biomass removal: BO = bole-only, WT= whole tree, WT+FF= whole tree + forest floor/ leaf litter. Compaction represents none, moderate, and severe as described in "Methods." Vegetation Control indicates whether herbicide was applied (VC) or not applied (No VC). Error bars represent +/- SEM. Within treatments, probabilities that share a letter are not significantly different. Whole-tree removal significantly decreased survival probability, and compaction treatments increased survival probability. No other effects were significant.

Growth

Vegetation control significantly increased heights of all species (p<0.001). In northern red oak, heights of trees in VC plots averaged 32% higher than no-VC; white oak height nearly doubled with VC from 424 cm to 837 cm; shortleaf pine height increased by 9% (119 cm) in VC treatments (Figure 5).

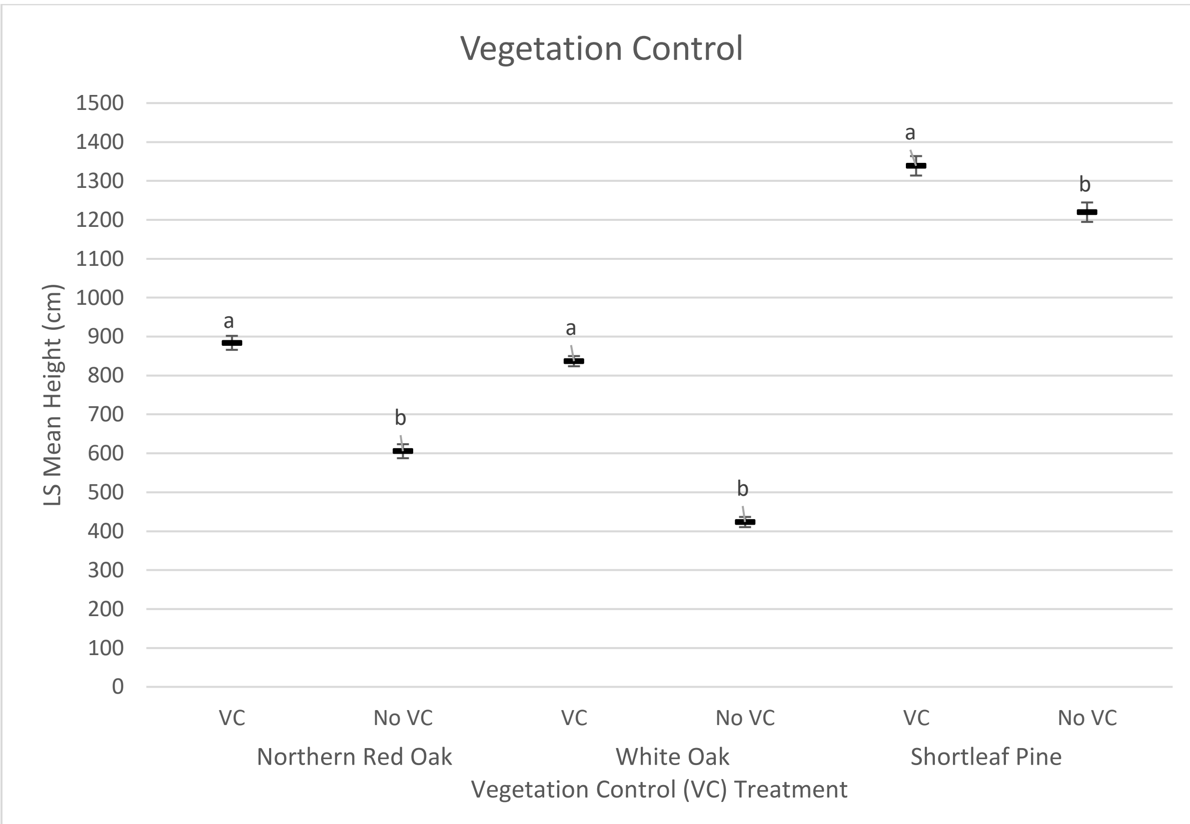

Figure 5. Vegetation control (VC) effects on northern red oak, white oak, and shortleaf pine. Error bars represent +/- SEM. For all species, the presence of an understory significantly reduced average height. On average, northern red oaks were 32% shorter with an understory; white oaks were 49% shorter, and shortleaf pines 9% shorter.

Compaction significantly increased the height of white oak (p=.001), and marginally increased the height of shortleaf pine (p=0.056), but did not affect northern red oak (p=0.174) (Figure 6). Biomass removal was marginally significant for shortleaf pine (p=0.038), where whole-tree removal decreased average height, while whole-tree plus forest floor removal increased average height. Biomass removal was not significant for northern red oak (p=0.357) or white oak (p=0.643) (Figure 6). The interaction of compaction x VC was significant in white oak (p=0.002) and shortleaf pine (p=0.006) but not northern red oak (p=0.704) (Figure 7). Overall treatment effect (biomass removal x compaction x VC) was marginally significant for shortleaf pine (p=0.035) but not northern red oak (p=0.401) or white oak (p=0.905). No other interactions for any species significantly affected height (p>0.100).

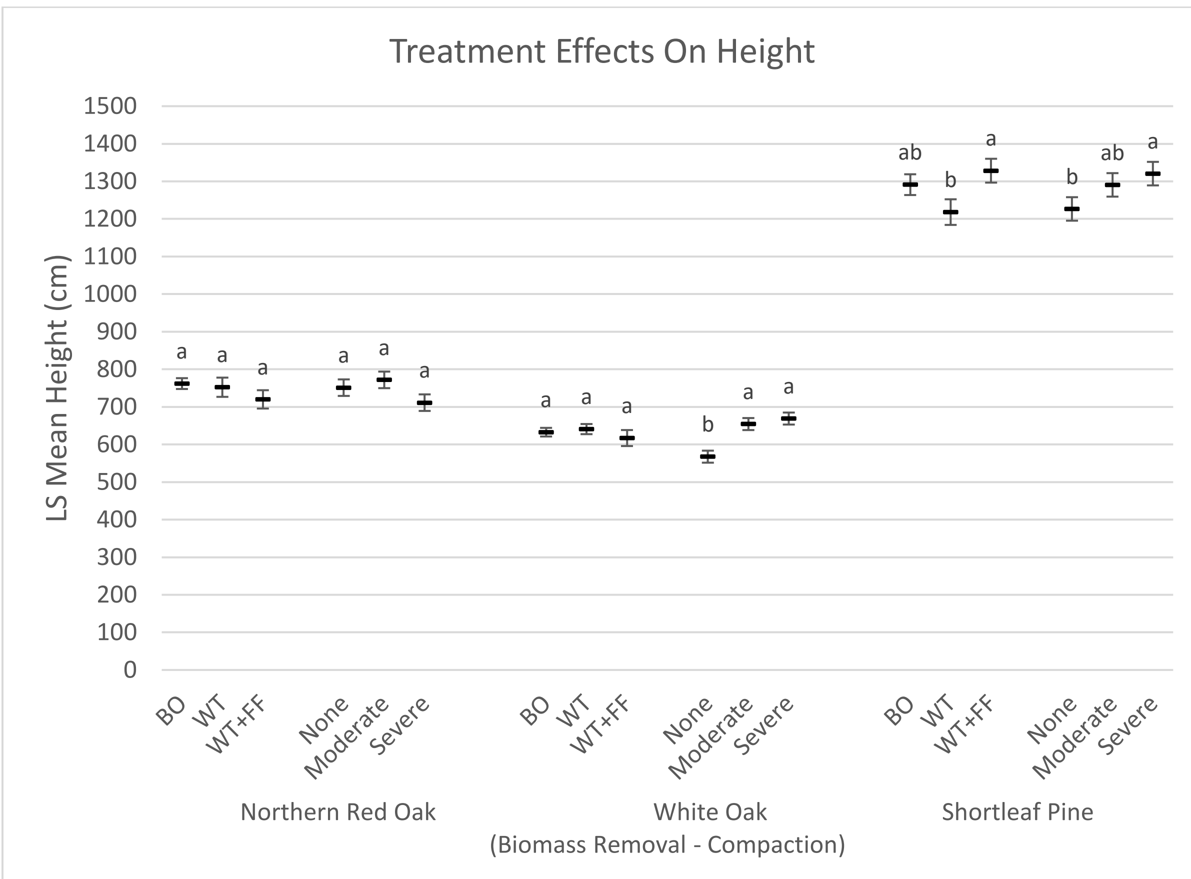

Figure 6. Treatment main effects on 22nd-year height for all three species. For biomass removal: BO = bole-only, WT= whole tree, WT+FF= whole tree + forest floor/ leaf litter. Compaction represents none, moderate, and severe as described in "Methods." Error bars represent +/- SEM. Within species, values that share a letter are not significantly different. Compaction significantly increased heights in white oak and shortleaf pine but was not significant in northern red oak. Whole-tree biomass removal decreased average shortleaf pine heights while whole-tree + forest floor removal increased average height. No other main effects were significant for any species.

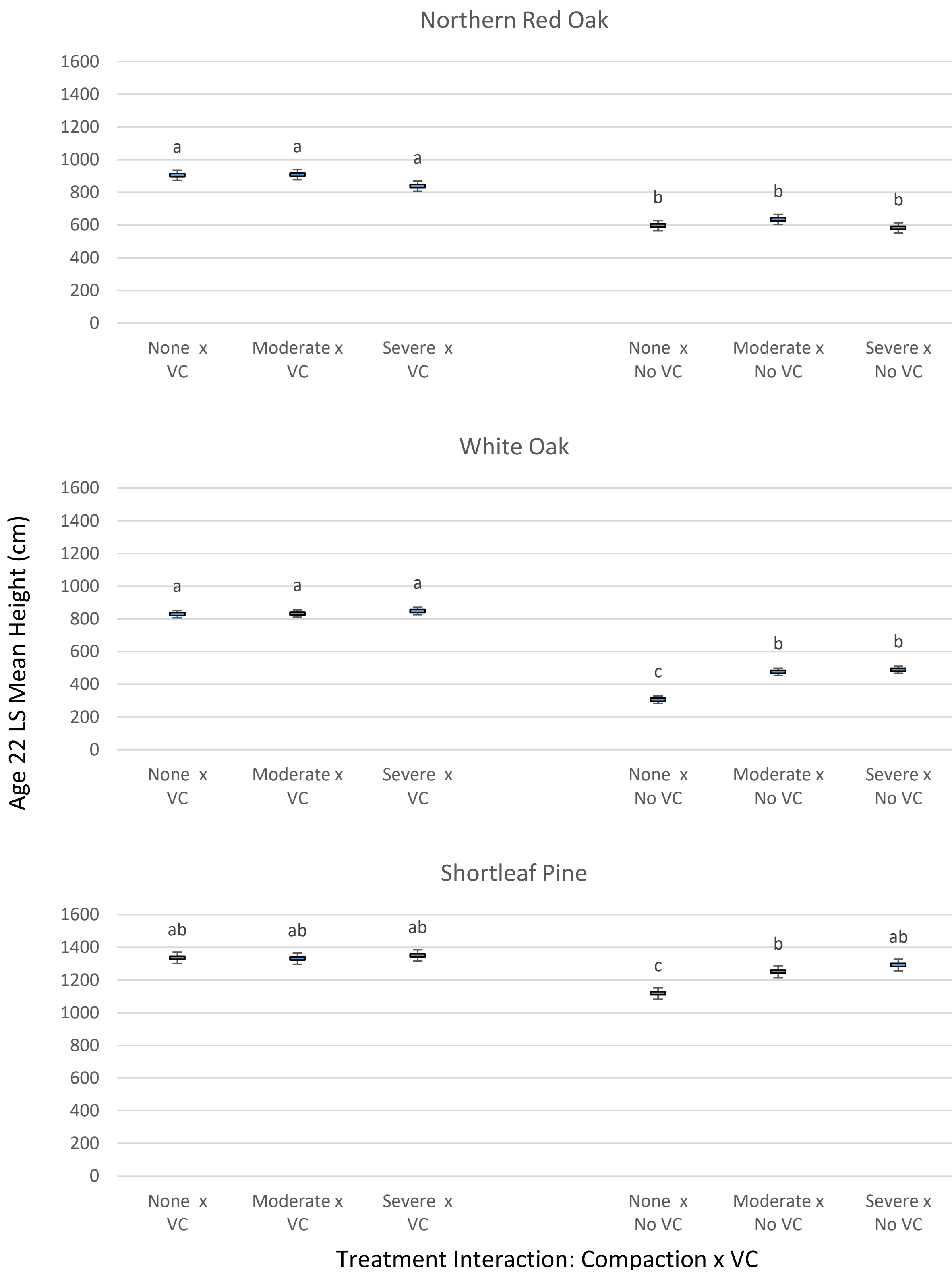

Figure 7. Least-square mean heights at age 22 for northern red oak, white oak, and shortleaf pine by treatment interaction of compaction (none, moderate, severe) x vegetation control (VC). The interaction was not significant for northern red oak (p=0.704), but was significant for both white oak (p=0.002) and shortleaf pine (p=0.006), where compaction increased heights in no-VC plots.

Long-term trends

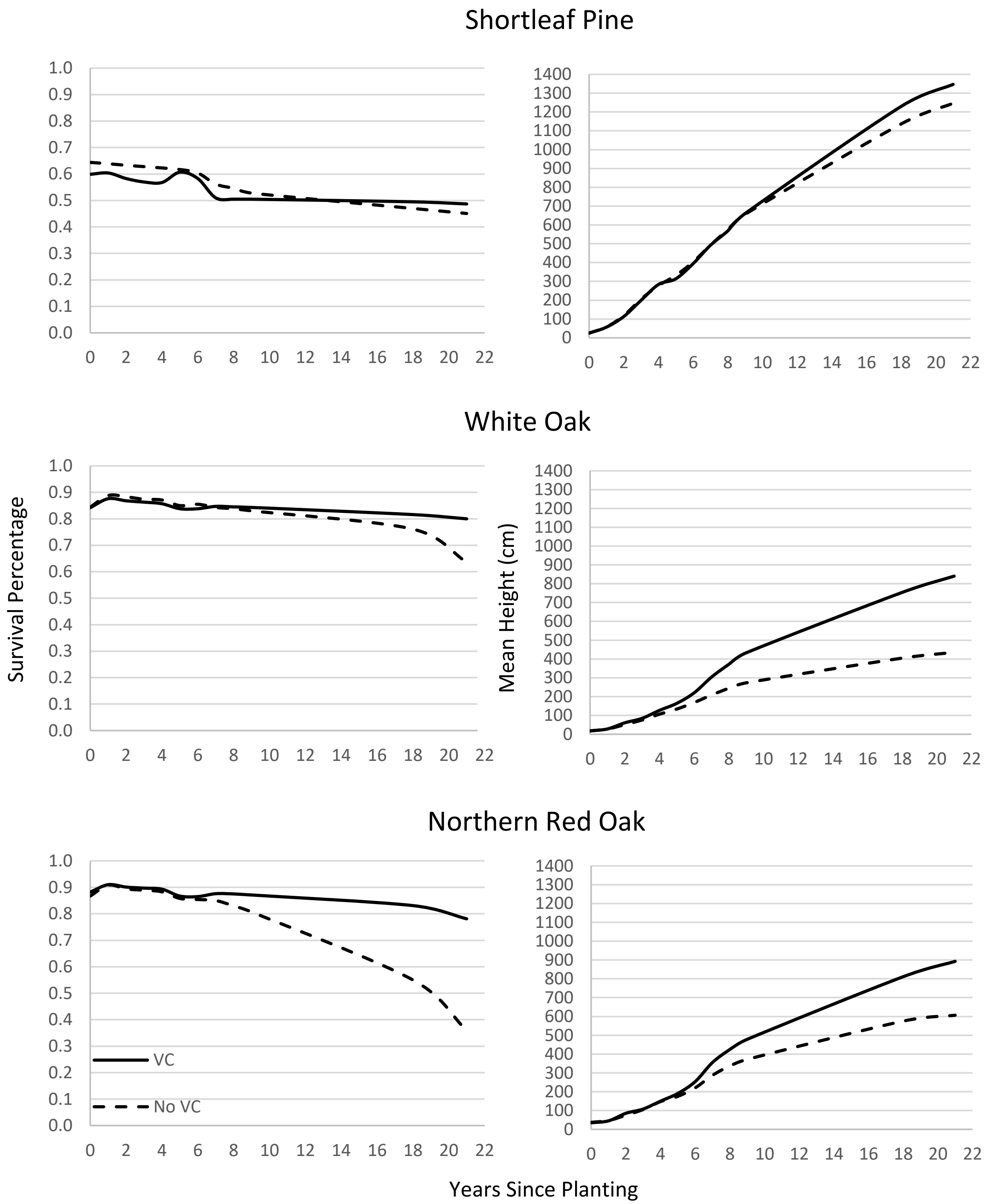

Figure 8. Actual survival and height growth from planting through year 22 for shortleaf pine, white oak, and northern red oak by vegetation control (VC) treatment. Survival remains consistent through time for shortleaf pine regardless of VC, while white oak and northern red oak survival decreases in the No VC treatment. Height follows a similar pattern, with shortleaf pine marginally affected through time, while both oak species experience significant growth reductions with no-VC.

Discussion

Vegetation control

Understory vegetation control had the most significant effect, increasing the twenty-two-year growth and survival of both oak species, while only increasing height growth in shortleaf pine. The presence of understory competition reduced mean height growth of northern red oak, white oak, and shortleaf pine. Survival probabilities were also significantly reduced in oaks by the presence of an understory with reductions for northern red and white oaks. Vegetation control was not a significant factor in shortleaf pine survival probability, though overall survival probability was nominally reduced when an understory was present.

Survival numbers were also affected when a total of 34 shortleaf pines were removed (harvested) from the site following the 6th growing season after abnormal growth was noted due to ice damage occurring during the previous year. All but one of these trees were in VC plots (Ponder 2007). Since we do not know the plots from which these trees were removed, it is possible that this ice storm, or other extreme weather conditions, disproportionately impacted shortleaf pine survival in plots that did not receive compaction treatments and where only the sawlog was removed, as survival probability averaged only 0.25 after 22 years (Figure 2). Ponder (1997) reported that due to a drought at time of planting, short-term irrigation was applied. These non-treatment effects may have increased the survival of shortleaf pine, as the survival probability in moderately compacted plots were statistically the same between vegetation control (0.53) and non-vegetation control (0.52) but were significantly higher in severely compacted plots when an understory was absent

(0.62 probability) than when an understory was present (0.51 probability). Similarly, Kabrick et al. (2015) found no correlation between shortleaf pine survival rates and overstory competition, suggesting additional contributing factors influencing the survival of this species. Vegetation control, though only significant for northern red and white oak survival probabilities, appears to have removed the effects of competition for light, water, and nutrients, allowing the seedlings time to become established. Long-term data show northern red oak survival for VC and non-VC plots are consistent until age 9, when a divergence begins (Figure 8). For northern red oak, survival decreases through time as the understory develops in non-VC plots, while the survival in VC plots remain consistent. White oaks exhibit more resilience and tolerance to understory competition through time, as their survival remains consistent through age 19 before decreasing significantly in non-VC treatments (Figure 8). Shortleaf pine survival was more variable through time than either oak. Survival probabilities in non-VC plots were higher than VC plots through age 10 before declining slightly. In VC plots, however, the survival reached at age 8 remained consistent through age 22 (Figure 14). Weather factors resulting in an initial mortality of 29% coupled with the removal of a significant number of trees after year 6 may inaccurately reflect the survival potential of shortleaf pines at this site.

Soil compaction

Soil compaction treatments had either no significant impact on mean height growth (northern red oak), or compaction actually increased mean height (white oak and shortleaf pine). Compaction consistently and significantly increased survival probability in all species, but notably in shortleaf pine, where severely compacted soils had a 22-year survival probability of 0.57, while non-compacted survival was only 0.33. These long-term findings in survival reverse a trend at this LTSP installation reported by Ponder (2007), who found 9-year survival probability of shortleaf pine seedlings decreased with increasing compaction (though those decreases were not significant). Schubert et al. (2004) found mean shortleaf pine survival of 56.2% after 22 years on Highland Rim sites in Tennessee. Those results were related to spacing in conifer plantations, which had a similar planting scheme as our study. Though conifer response to compaction is generally positive (Brais 2001, Gomez et al. 2002, Power et al. 2005, Ponder et al. 2012), it was notable that northern red and white oak survival probabilities, and white oak height growth were also positively affected by compaction. Compacted forest soils typically require several decades to recover a non-compacted bulk density (Sands et al. 1979). Recovery can be affected by several factors, namely repeated exposure to compacting events (i.e. tree/biomass harvesting), soil moisture, coarse fragment content, and cryoturbation (Liechty et al. 2002). The Clarksville series soil found at this site can contain as much as 80% coarse fragments, providing a buffer of sorts to resist compaction of the fine-earth portion of the soil. Additionally, the Missouri site was also exposed to sampling error from the collection method, which may have under-reported initial soil bulk densities at study initiation, possibly impacting future analyses (Lichter and Costello 1994, Ponder 2007). However, subsequent bulk density measurements were taken using the polyurethane foam method and showed complete amelioration of bulk density after 10 years (Ponder et al. 1999, Ponder 2007, Ponder et al. 2012).

Biomass removal

The absence of any long-term height reduction in red and white oaks under increasing levels of biomass removal is notable. Both oak species responded with increased height growth to whole-tree removal over sawlog removal. The removal of the forest floor biomass caused no significant reduction in height. Shortleaf pine heights, however, decreased significantly with whole-tree removal, only to rebound and exceed sawlog-only height growths under the more intensive biomass removal treatment. Given that trend, it is possible the reductions in growth from whole-tree removal were an anomaly caused by other factors. The consistency in adverse effects on height growth and survival for whole-tree harvesting in shortleaf pine may warrant additional consideration, however. The overall trends of height growth remain consistent across the three species. These findings generally follow with 10-year total biomass analyses across the LTSP network where Ponder et al. (2012) found no differentiation among organic matter removal treatments. Upland oaks and shortleaf pine tend to dominate nutrient-poor and droughty sites throughout their respective ranges (Brinkman and Rogers 1967, Cain and Shelton 2000, Kabrick et al. 2015). The ability to historically thrive under generally poor conditions may be why height growth and survival are less adversely affected by nutrient (biomass) removal from this site. Though this resilience could be a function of the youth and vigor of the stand, oaks and shortleaf pine are also particularly adapted to harsh site conditions.

Interactions

The survival probabilities of all species were affected by two interactions: compaction by VC, and compaction by biomass removal. In both oak species, compaction increased survival probability in no-VC plots; while shortleaf pine survival probability was increased by compaction in both VC and no-VC plots. Where biomass removal interacted with compaction, results were more variable. Northern red oak survival increased with moderate and severe compaction in the sawlog and whole-tree removal treatments, but compaction had a neutral or negative effect when the whole-tree plus forest floor/leaf litter were removed. White oak behaved similarly, though compaction had a less significant effect in the most extreme biomass removal treatment. In all levels of biomass removal, shortleaf pine survival was increased by compaction (Figure 8).

Growth was less affected by interactions than survival, with the compaction by VC interaction significantly impacting white oak and shortleaf pine. Height growth of white oak and shortleaf pine was increased by compaction in no-VC plots, but unaffected in VC treatments. This interaction did not affect northern red oak.

The equipment used to compact the site may have contributed to these results, as multiple passes with heavy construction equipment would likely disturb the soil enough to alter or suppress the seedbed and the sprouting ability of hardwood stumps, ultimately serving as a de-facto understory control agent. Similarly, the complete absence of major soil disturbance in plots that did not receive compaction treatments, and the use of non-contact harvest methods (i.e. cable yarding system), would allow the existing seedbed to immediately respond to the open growing conditions following harvest, reducing available resources for the newly planted seedlings. However, we recommend further analysis of this site and other LTSP installations to support or refute this conclusion.

Conclusion

Vegetation control had the greatest impact on seedling survival and growth, significantly increasing the oak survival and growth, and significantly increasing the growth of shortleaf pine. This suggests that a significant barrier to seedling survival and growth is competition from other trees in the understory. Compaction also affected survival and growth, but in unexpected ways by increasing the growth of shortleaf pine and white oak and having no significant effect on the growth northern red oak. These results may be due to the high coarse fragment content of the soils in the Ozark Highlands that may protect the soil from the negative effects due to compaction, thus mitigating deleterious effects caused by harvesting equipment. The lack of long-term decreases in productivity associated with site biomass removal suggests that excessive nutrient removals associated with practices such as biomass harvesting will have few measurable effects when conducted only one time. However, reductions in survival or growth due to nutrient losses associated with biomass harvesting may not be realized for several rotations. The LTSP program continues to provide valuable information for scientists and land managers. Installations throughout the program should continue to be monitored to continually increase available data on tree survival and growth.

Acknowledgements

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Chapter 4:

Increasing survival probability, height growth, and diameter growth of 1-0 shortleaf pine (*Pinus echinata)* seedlings through genetic selection, site preparation, and vegetation control

Stephen Lyczak

Abstract

Natural regeneration of shortleaf pine has proven difficult due to slow growth, high mortality, and lack of competitive ability. Consequently, artificial regeneration is commonly used for reforestation, although regeneration failures are common. We examine how genetic selection, in conjunction with extensive site preparation and understory vegetation control, can increase reforestation success. We used data from three long-term studies in southeastern Missouri to examine survival of 5,000 1-0 shortleaf pine seedlings. One site contains 2,000 full-sib plus 1,000 orchard-run 1-0 containerized seedlings planted on a mechanically cleared hillslope. Herbicide was applied to 2,000 seedlings at initial planting, and one-year after planting, while 1,000 seedlings received no herbicide. In addition, 2,500 orchard-run, bareroot seedlings were planted at two similar sites: one utilizing herbicide understory control for 10 years, and one underplanting in an existing forest with no site preparation or herbicide. Survival 7 years after planting ranged from 30% for underplanted seedlings to 99% in pedigree seedlings with herbicide application and site preparation, or when seedlings were taller than an identified competitor. Height growth was significantly greater in several pedigrees, however, there were no significant differences between the majority of pedigrees and orchard-run seedlings. Overstory stocking levels above 15% did significantly reduce height. Diameter growth was significantly reduced by the presence of an overstory >15% and all understory competition.

Introduction

Shortleaf pine (*Pinus echinata* Mill.) has the widest range and distribution of any southern pine in the United States, found in at least 22 states from New York and New Jersey in the northeast, to Oklahoma and Texas toward the southwest. It is the only pine species native to Missouri, naturally occurring throughout the southern, and southeastern areas of the state (Liming 1946, Brinkman and Rodgers 1967), where it is commonly found as a component of varying significance with oaks (*Quercus* spp.*)*, hickories (*Carya* spp.), and other hardwoods (Moser et al. 2007). Though not generally a commercial species of interest, restoration of shortleaf pine is a priority throughout Missouri to increase wildlife diversity and forest resilience (Eddleman et al. 2007, Kabrick et al. 2015). Artificial and natural regeneration methods have encountered mixed success due to fire suppression, understory competition, lack of seedling establishment, and slow seedling growth (Lawson 1990, Gwaze et al. 2006, Jensen et al. 2007, Stambaugh et al. 2007).

There is a need to identify methods for increasing the early survival and growth of shortleaf pine seedlings. Though considerable research into site preparation methods, spacing, herbicide use, and genetics exist for loblolly (*Pinus taeda* L.), slash (*P. elliottii* Engelm.), and longleaf (*P. palustris* Mill.) pines (see Lewis et al. 1985, Baldwin, Jr. et al. 2000, Raley et al. 2003, Land, Jr. et al. 2004, Schubert et al. 2004, South et al. 2004), there is less current research into these practices for shortleaf pine (Gwaze et al. 2005, Gwaze et al. 2006, Studyvin and Gwaze 2007, Smith 2011). Our objectives are to assess the effects of genetic selection, site preparation, and vegetation control on the 1st and 7th year survival, height growth, and diameter growth of planted 1-0 shortleaf pine seedlings.

Methods and Data Analysis

Site Descriptions

Three data sets were used for this study. The first was from a study conducted at the *Wurdack Research Center* in Crawford County, MO (*N 37°47'23.9", W 91°25'12").* The site is a continuous, south-facing slope of 10-30%, with two soil series occurring: Reuter, a loamy-skeletal, siliceous, active, mesic Typic Paleudalfs on the upper and lower backslopes, and Goss, a clayey-skeletal, mixed, active, mesic Typic Paleudalfs occurring on lower slope positions (NRCS *Web Soil Survey* 2017). The second study was conducted at the *Long-Term Soil Productivity site* (LTSP), Shannon County, MO (*N 37°10'47.9", W 91°6'35.9")*. Soils on site are primarily of the rocky, nutrient-poor Clarksville series (loamy-skeletal, siliceous, semi-active, mesic Typic Paleudults), formed from hillslope sediments and cherty residuum from dolomite (NRCS *Web Soil Survey* 2017). The third study was conducted at *Sinkin Experimental Forest*, Reynolds and Dent Counties, MO (*N 37°29'24", W 91°15'36")*. Soils include the Clarksville and Coulstone series, both loamy-skeletal, siliceous, semi-active, mesic Typic Paleudults, as well as the Nixa series, a loamy-skeletal, siliceous, active, mesic Glossic Fragiudults (NRCS *Web Soil Survey* 2017). At all three sites, the site index (base age 50) for shortleaf pine was between 17.1 m and 18.3 m (California Soil Resource Lab *SoilWeb* 2017). Thus, height and diameter growth differences among the three sites were likely due to treatments rather than site factors.

At Wurdack, seedlings consisted of genetically improved, 1-0 containerized shortleaf pine stock representing 12 full-sib families, plus standard, orchard-run seedlings from the state nursey at Licking, MO. Families were crossed from elite parents selected in natural stands on the Mark Twain National Forest in the 1970s (Gwaze et al. 2005, Smith 2011). The existing hardwood forest was clearcut in 2008, and a masticator was used to grind tree stumps and non-merchantable material in 2009. The site was then divided into four blocks. Seedlings were deployed in complete blocks in 2010, with 700-1000 seedlings per block. Three blocks had a silvopasture treatment applied, which involved a double row of trees spaced 3.05m x 3.05m followed by a 12.19m wide alley. A mix of native warm and cool season grasses were broadcast seeded into the alleyways after seedling planting. Herbicide pellets (Velpar®) were applied to the seedling planting rows for two years following planting. The fourth block eliminated the alley, leaving rows evenly spaced at 3.05 meters. No herbicides were applied in this block and no grasses were seeded. Instead, an additional 12 families (not replicated in the other three blocks) were selected and planted along with the 12 replicated families. Tree heights and diameters were measured in 2010, 2011, and 2017. For purposes of this analysis, trees planted in the no herbicide treatment will be identified as either genetically improved ('Genetic'), or orchard-run ('No Genetic').

At the LTSP, a 3x3, split-plot factorial study design, to simulate harvest-related soil disturbances, and consisting of organic matter (biomass) removal, soil compaction, and vegetation control was established in 1995, following a nationally implemented protocol that dictated methodology (Powers et al. 1990, Ponder and Mikkelson 1995). Three levels of organic matter removal included: removal from site of tree boles only, whole tree (bole, top, limbs), and whole tree plus forest floor (tree bole, top, limbs, and raking of forest floor to remove the organic soil horizon). Three levels of soil ("whole-soil") compaction were implemented: no compaction (average bulk density of ~1.30 g/cm^3), moderate compaction (average bulk density ~1.60 g/cm^3), and severe compaction (average bulk density ~1.80 g/cm^3). In addition, half of each treatment plot had chemical herbicide applied annually for 10 years following seedling planting. Bare-root, 1-0 northern red oak (*Quercus rubra* L.), white oak (*Q. alba* L.), and shortleaf pine (*Pinus echinata* Mill.) were planted following the application of the treatments (only shortleaf pine data are included in these analyses). Tree height and diameter (basal diameter or diameter at breast height, depending on tree height) were collected annually from 1995 until 2004, with additional collections in 2013 and 2016. For additional information on study design, plot layout, and site characteristics, see Ponder and Mickelson (1995) and Lyczak (2019).

At the Sinkin Experimental Forest, the treatment involved the manipulation of overstory stocking levels to between 0-73 percent based on Gingrich (1967). After the desired plot densities were obtained, 1-0 bareroot shortleaf pine seedlings were underplanted in the residual mixed hardwood stand in 2008. A windstorm one year after seedling planting removed additional overstory trees in some treatment plots, lowering the overstory density and residual basal areas per plot. In order to determine the effects of competition on shortleaf pine seedlings, the nearest hardwood competitor was identified, tagged, and measured. Seedlings shorter than their corresponding hardwood competitor were analyzed irrespective of overstory stocking level. Hardwood competitors were from either advance reproduction or stump sprouts. Pine height and diameter (basal diameter or diameter at breast height, depending on height) were collected in 2008, 2009, 2010, 2013, and 2017. Identified hardwood competitors were measured in 2010, 2013, and 2017. For additional information on study design, plot layout, and site characteristics, see Kabrick et al. (2011).

Data Analyses

For each planting site, survival probabilities in relation to pedigree, vegetation control (VC), or overstory treatment were determined using logistic regression for the 1st and 7th-year data collection (Table 1). We used a generalized linear mixed model with a binary distribution (survival =1, mortality =0), logit link function, and random intercept using PROC GLIMMIX in SAS 9.4 software (SAS Institute, Inc., Cary, NC).

Table 2. Description and breakdown of primary treatment, vegetation control parameters, and tree count (*n)* used in analyses, by site.

Site	Primary Treatment	Vegetation Control (VC)	*N*
Wurdack	Pedigree	Yes	736
Wurdack	Pedigree	No	756
Wurdack	No Pedigree	Yes	872
Wurdack	No Pedigree	No	408
Sinkin	Stocking level <15%	No	480
Sinkin	Stocking level 15-45%	No	510
Sinkin	Stocking level >45%	No	540
LTSP	N/A	Yes	384
LTSP	N/A	No	379

Treatment effects on tree heights were analyzed using a generalized linear mixed model with a lognormal distribution, identity link function, and no intercept, using PROC GLIMMIX in SAS 9.4 software (SAS Institute, Inc., Cary, NC). We used linear regression to identify relationships between tree heights and pedigree, VC, or overstory treatment. Least-square means of tree heights were subjected to pairwise comparisons using T-grouping at *alpha*=0.05.

Results

First-year survival probability was greater than 95 percent for most sites, treatments, and families (Figure 1). Wurdack trees with no vegetation control had mean survival of probability of 75 percent regardless of genetic origin. At the LTSP installation, both treatment groups had survival probabilities just over 60 percent, as did Sinkin trees that were shorter than their nearest competitor. Pedigree, VC, or overstory treatment were a significant effect (p<0.001).

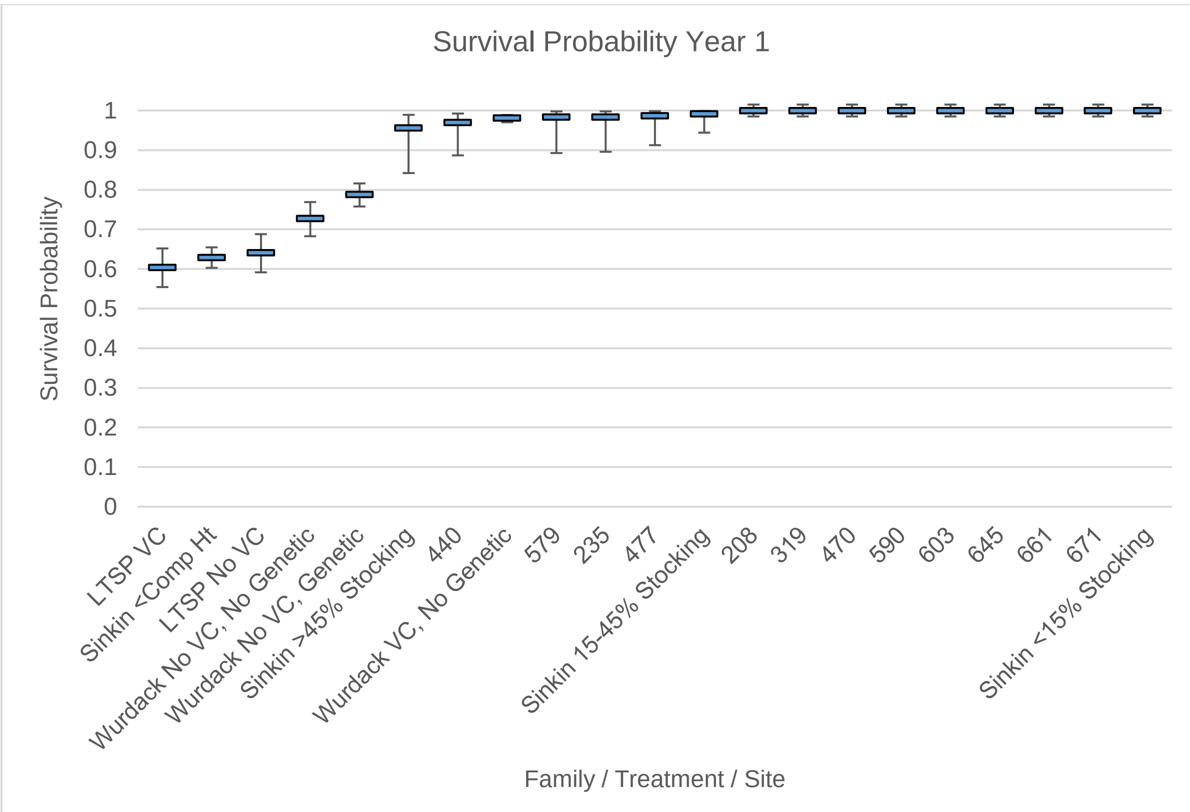

Figure 4. Survival probability 1 year after planting by either family number (for Wurdack trees), or treatment (Wurdack orchard-run trees with herbicide treatment, LTSP, and Sinkin trees). Error bars represent +/- standard error of the mean (SEM). X-axis categories are as follows: LTSP VC= trees grown at LTSP where chemical vegetation control was used; LTSP No VC= LTSP site with no chemical vegetation control; Sinkin <Comp Ht= trees underplanted at Sinkin that were less than 80% of the height of the nearest competitor; Sinkin >45% Stocking= Sinkin trees greater than 80% of the nearest competitor in height, with an overstory stocking level of 45% or more; Sinkin 15-45% Stocking= trees underplanted at Sinkin, greater than 80% of competitor height, with an overstory stocking between 15-45%; Sinkin <15% Stocking= Sinkin trees within 80% of competitor height with an overstory of 15% or less; Wurdack VC, No Genetic= Orchard-run seedlings planted with herbicide application; Wurdack No VC, Genetic= Trees belonging to one of the 12 genetic families at Wurdack, but planted with no herbicide applied; Wurdack No VC, No Genetic= Orchard-run seedlings planted with no herbicide applied; All other numbers= genetic family of trees planted at Wurdack. With the exception of LTSP, survival probability is less than 95% where either understory or overstory competition is present. LTSP experienced high year-1 mortality due to unique site conditions at time of planting.

Survival probability in year 7 approached or reached 100 percent for all Wurdack families in the VC treatment, as well as all Sinkin trees taller than their nearest competitor (Figure 2). Where an understory was present at Wurdack, survival probability was 71 percent. At Sinkin, a taller competitor reduced survival probability to 35 percent. Survival probability at LTSP was lower in VC plots (51 percent) than no-VC plots (56 percent), but this difference was not significant (p=0.294). Several categories experienced an increase in survival probability from year 1 to year 7 from stump sprouts following damage or mortality in the intervening years. Pedigree, VC, or overstory treatment were significant (p<0.001).

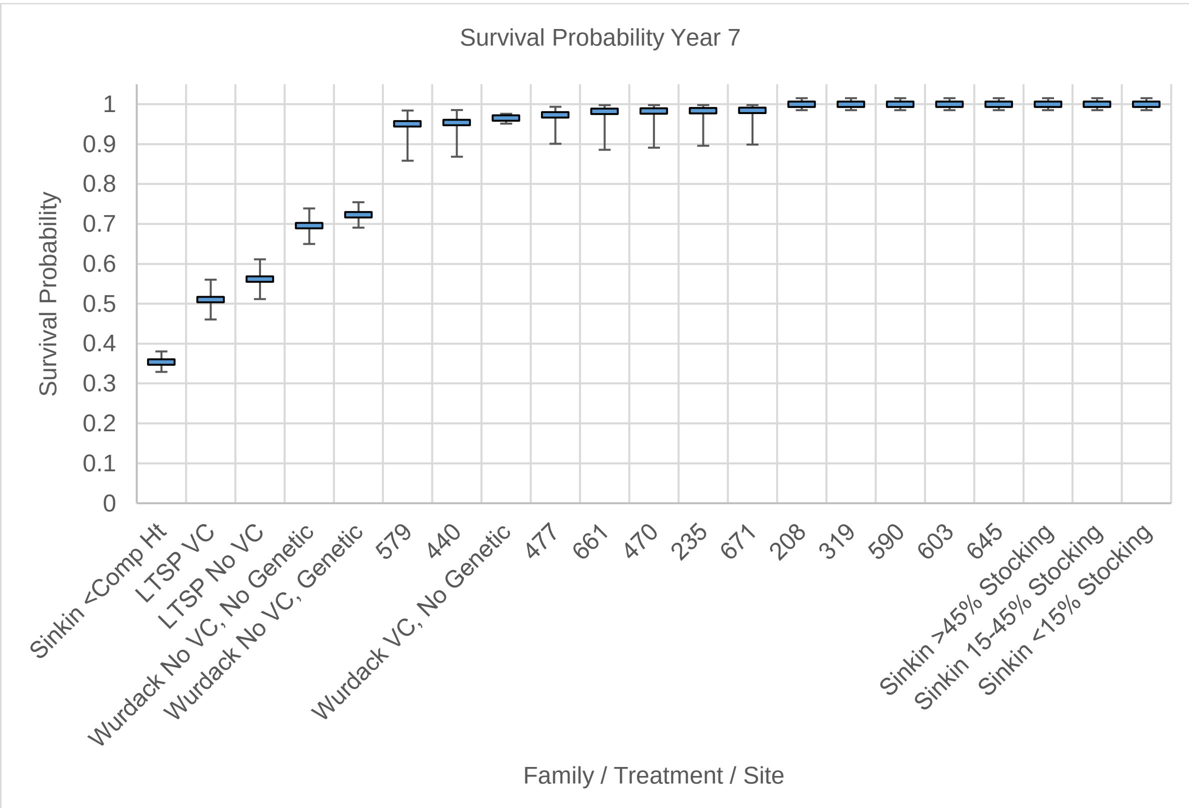

Figure 5. Survival probability 7 years after planting. Categories of classification are the same as in Figure 1. Error bars represent +/- SEM. Some probabilities may be higher than year 1 due to stump sprouting between measurements. Sinkin trees within 80% of their competitor's height, as well as all Wurdack trees in silvopasture plots with herbicide have survival probabilities above 95%. When herbicide was not applied and spacing reduced at Wurdack, survival probability dropped to 71%. Sinkin trees shorter than their competitor had a 35% survival probability. Following high year-1 mortality, LTSP survival probability is just above 50%.

Mean height in year 1 was highly variable across treatments (Figure 3). In underplanted sites with an overstory stocking >15 percent, mean height was 29cm. Reducing the overstory stocking below 15 percent significantly increased mean height to 44cm. There was no significant difference in height between herbicide treatments at LTSP, where first-year height averaged 55cm. Genetic improvement without herbicide or site preparation significantly increased mean heights to 70cm. The addition of herbicide and site preparation provided a further significant increase to mean height, with a first-year mean of 84cm. The top five families had a mean height of 96cm, and were significantly taller than all other treatment groups.

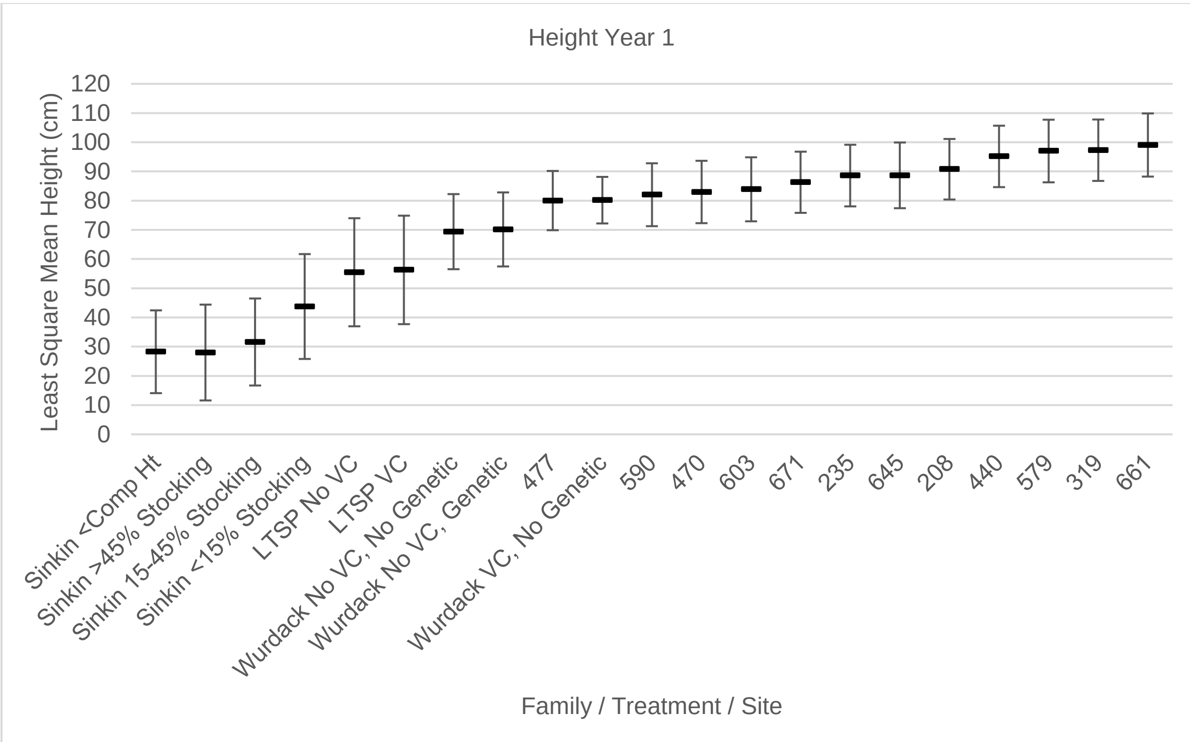

Figure 6. Mean tree height 1 year after planting. X-axis categories follow Figure 1. Error bars represent + / - SEM. Four genetically improved families were significantly taller than all others: 440, 579, 319, and 661. There was no significant difference between the other Wurdack families and non-improved seedlings (family '1'). Pedigree seedlings planted without herbicide were significantly shorter, however. Herbicide did not affect height at LTSP. The presence of an overstory >15% significantly reduced heights when seedlings were underplanted. Underplanted trees in clearcuts (overstory <15%) were significantly shorter than pedigree trees and seedlings with herbicide, but significantly taller than trees with a dense overstory.

Year 7 heights were significantly affected by treatment ($p<0.001$) (Figure 4). Underplanted seedlings shorter than the height of the nearest competitor were significantly shorter than all other groups, with a mean height of 84cm. When underplanted seedlings were within 80 percent of competitor height, but with an overstory >45 percent stocking, mean height increased to 120cm. Reducing overstory stocking to between 15-45 percent significantly increased mean height to 253cm. When the overstory was eliminated, mean height was statistically similar to all but the top five pedigreed families, with an average of 463cm.

Herbicide application and site preparation methods did not significantly affect year 7 height, however, the top five families were significantly taller than all other treatments, averaging 503cm after seven years.

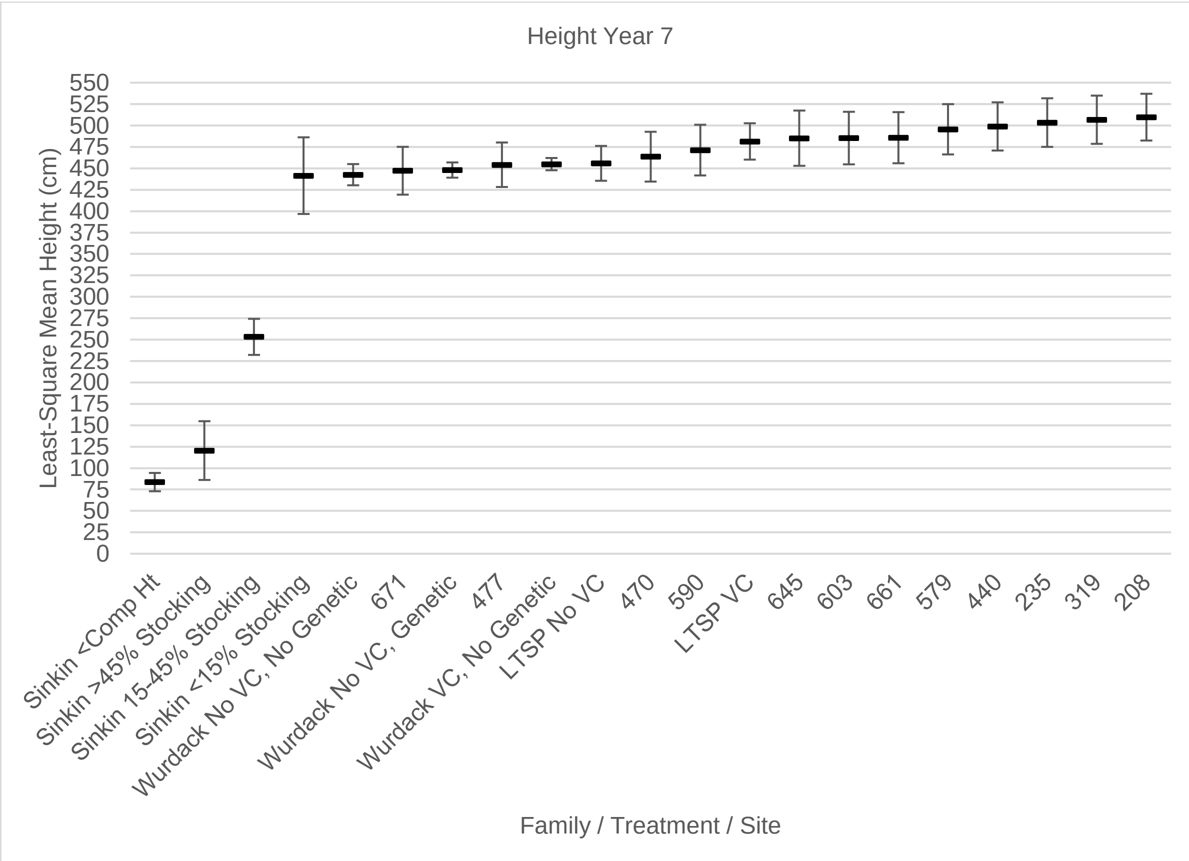

Figure 7. Mean tree height 7 years after planting. Treatment categories reflect Figure 1 definitions. Error bars represent +/- SEM. While the presence of an overstory (>15%) greatly reduced tree height, seedlings planted in clearcuts were not significantly shorter than unimproved trees on herbicide/ prepared sites, and most pedigreed stock. Three families were significantly taller than all others: 235, 319, and 208.

Basal diameters in year 1 were significantly reduced by the presence of an overstory ($p<0.001$). When underplanted, mean basal diameter was 4.5mm. Pedigree stock without herbicides applied improved to a mean of 14mm. The addition of herbicide further increased mean basal diameter of pedigree seedlings to 19.6mm. Two families had a significantly greater basal diameter, with a mean of 24mm (Figure 5).

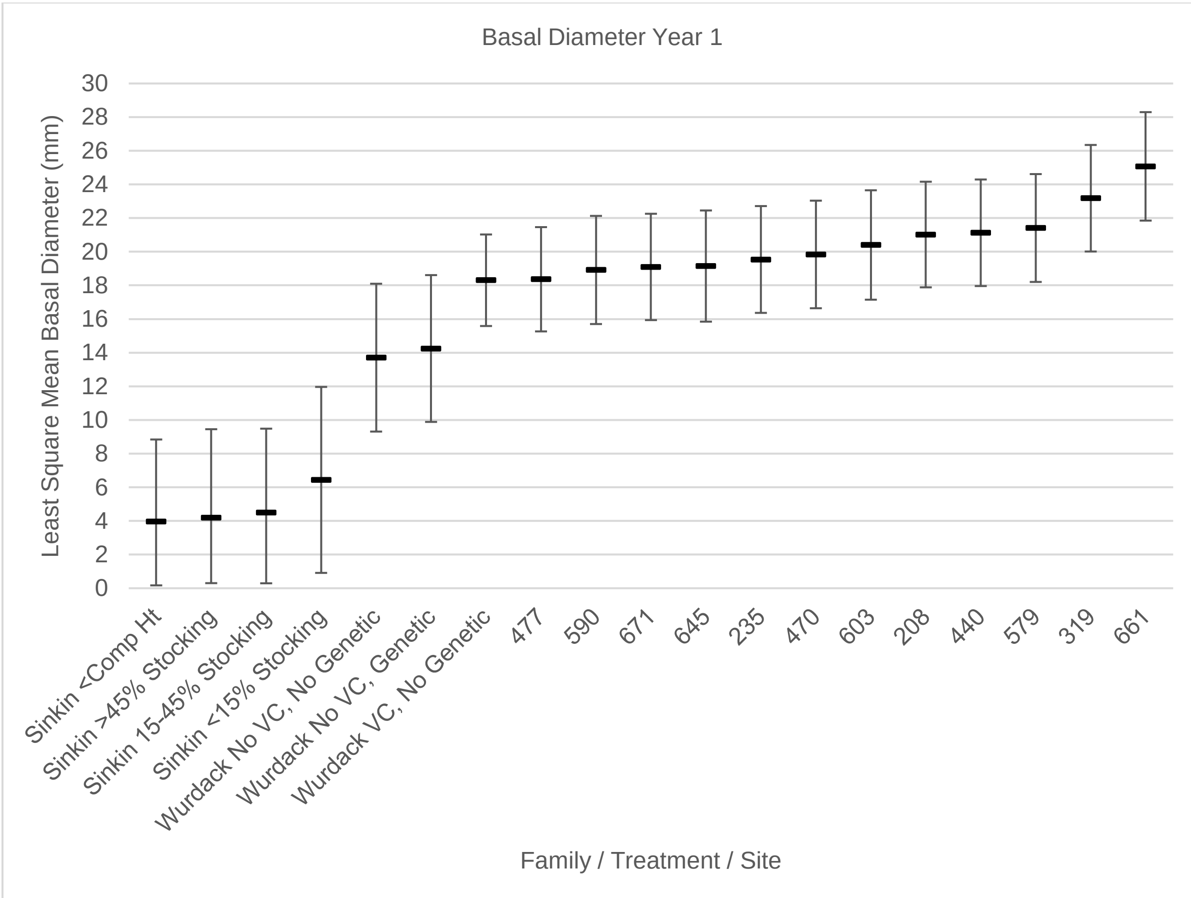

Figure 8. Year 1 mean basal diameter. Classifications follow definitions in Figure 1. Error bars represent + / - SEM. All underplanted trees, even clearcuts, had significantly lower basal diameters than sites where site preparation was used. The use of herbicide significantly increased basal diameter in pedigreed trees. Two families had a significantly higher basal diameter: 319 and 661. Note: Diameter readings were not recorded at LTSP until year three.

By year 7, diameter at breast height (DBH) was significantly increased by understory herbicide application ($p<0.001$). The following trends were observed: mean DBH in herbicide treatment was 98mm; pedigreed seedlings planted in non-herbicide plots had a mean DBH of 82.5mm; trees planted with overstory density <15 percent and no understory herbicide applied averaged 69mm DBH, significantly lower than both the pedigree seedlings, and those planted with herbicide treatments; the presence of a moderate overstory (<45 percent) reduced mean DBH to 41mm, while a dense overstory (>45 percent) had a mean DBH of just 16mm (Figure 6).

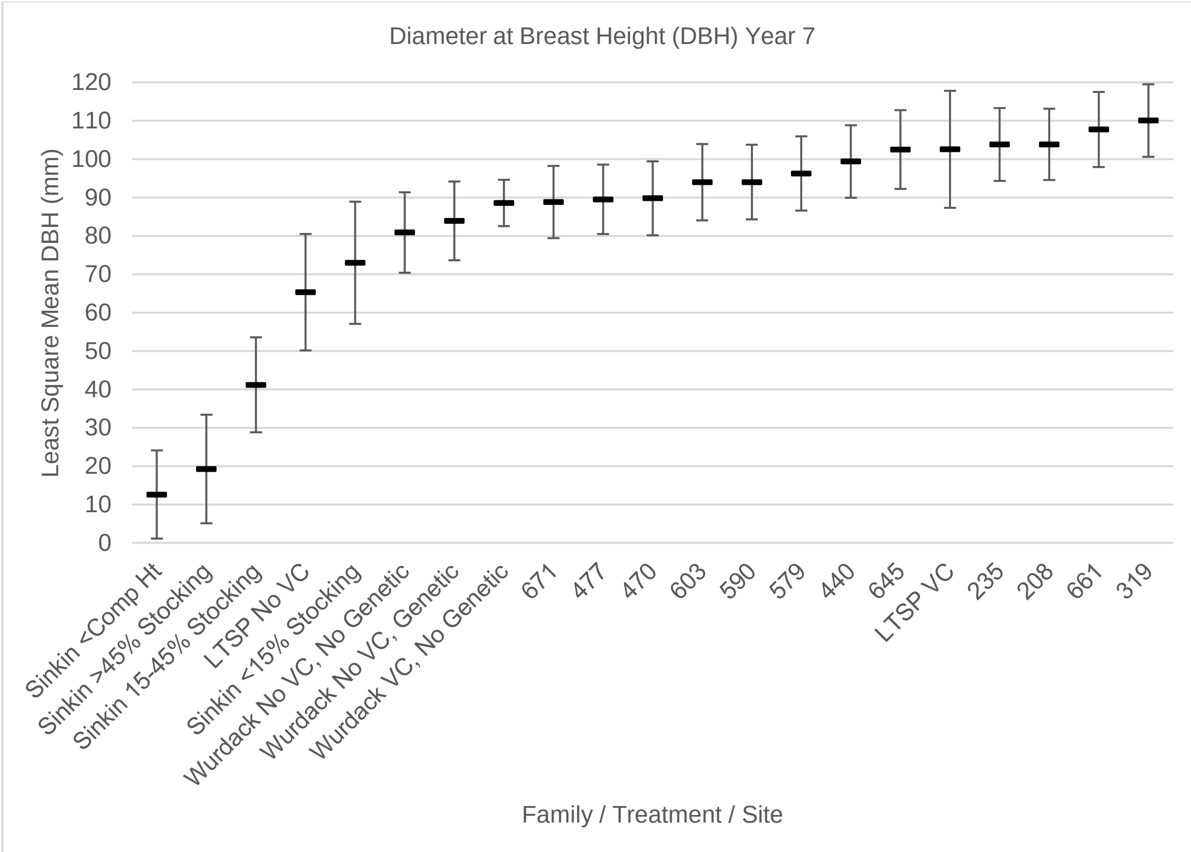

Figure 9. Year 7 diameter at breast height (DBH). Categories along X-axis are equivalent to those in Figure 1. Error bars represent + / - SEM. Understory competition was the most significant factor reducing diameter growth in year 7. All locations where herbicides were applied had significantly higher DBH values. Genetic improvement without herbicide resulted in a significant increase in diameter growth, while non-pedigree seedlings, especially those with overstory competitors, exhibited significantly reduced DBH growth.

Discussion

Survival

Shortleaf pine seedling survival at 1- and 7-years following planting was primarily affected by the presence of understory competition (Figures 1 and 2). This finding is similar to Blizzard et al. (2007), who reported that understory competition density had a greater effect on naturally regenerated shortleaf pine seedling survival than did overstory density. Similarly, Kabrick et al. (2015), reported overstory stocking had no significant effect on shortleaf pine survival. Genetic selection and site preparation do not appear to have consistently increased survival in this study, as underplanted seedlings within 80 percent of their competitor's height exhibited similar survival probabilities at Sinkin regardless of overstory density, while seedlings planted in prepared plots at LTSP had significantly lower survival than prepared plots at Wurdack (Lyczak 2019a, Lyczak 2019b). However, when pedigreed seedlings were planted without herbicide application, survival significantly decreased by more than 20 percent in year 1, and over 30 percent by year seven when compared to the same families in herbicide treatments at Wurdack, suggesting an opposite trend. These survival numbers are surprisingly and significantly lower than Brissette and Barnett (2003), who reported over 90 percent survival 10 years after planting on half-sib shortleaf pine in northern Arkansas. Other site preparation methods, including ripping and prescribed fire, also result in mean first-year survival rates >90 percent, suggesting a possible alternative to herbicide application (Cain and Shelton 2000, Gwaze et al. 2006). Though overall survival probability at LTSP was 60 percent, irrespective of herbicide application, this may be due to unique conditions encountered at planting, including drought and rodent damage. These conditions were remedied with irrigation and tree shelters respectively (Ponder 1997), though the long-term effect on survival is unknown.

Height Growth

Height growth is a highly heritable trait in shortleaf pine, according to a study of progeny selected from phenotypically superior wild trees at a first-generation seed orchard in Missouri (Gwaze et al. 2005). It was therefore surprising that we found only 2 of 12 full-sib families outperforming standard seedlings after 7 growing seasons. Pedigreed seedlings had significantly increased first year height growth of 15-40cm versus orchard-run seedlings

(Figure 3). By the seventh growing season, however, only 2 families (319 and 208) were significantly taller than orchard-run seedlings (Figure 4). Underplanted seedlings that were either shorter than their nearest competitor, or those with an overstory density >45 percent were significantly shorter than seedlings planted with either herbicide treatments, site preparation, or both at LTSP and Wurdack. Unlike survival, the presence of overstory >45 percent density significantly reduced mean height by nearly half, while being shorter than a nearby competitor, regardless of overstory density, resulted in a mean height reduction of almost 85 percent. Site preparation and herbicide application provided the most significant height growth gains, consistent with studies on other southern pines (see Lewis et al. 1985, Land, Jr. et al. 2004, Schubert et al. 2004, South et al. 2004). As these stands continue to develop, early height growth, especially that above competing vegetation, is an important element in evaluating whether shortleaf pine will recruit to the overstory upon canopy closure (Raley et al. 2003).

Diameter growth

Diameter growth followed a similar trend to that of height (Figures 5 and 6). Year 1 basal diameter was significantly greater in pedigree seedlings than other treatments, though seedling production and planting methods may account for these differences. Diameter data were not collected on the LTSP site until year 3, so we were unable to compare herbicide and site preparation treatments with the Wurdack seedlings. However, pedigreed seedlings planted without herbicide application at Wurdack had significantly smaller basal diameters (14mm) than pedigreed seedlings with herbicide application (21mm). Underplanted seedlings with any overstory had a 1/3 smaller basal diameter (4mm) than underplanted seedlings with an overstory <15 percent (6mm). By year 7, diameter at breast height (DBH) was significantly increased with herbicide applications, but not significantly affected by pedigree. Heritability estimates for diameter are lower than those for height, which is supported by these results (Gwaze et al. 2005). The presence of understory competition significantly reduced DBH, even when trees were taller than their nearest competitor (Sinkin) or as tall as site trees in herbicide plots (LTSP). As we found with height, high overstory density (>45 percent), or being shorter than a competitor severely reduced mean DBH values in underplanted seedlings. Diameter growth is less important than height growth during the stem exclusion stage of stand development, as suggested by Oliver and Larson (1996). However, larger diameters are associated with higher survival probabilities, increased resistance to fire and pest damage, as well as greater resilience to the effects of competition (Brinkman and Rodgers 1967, Brinkman and Smith 1968, Lawson 1990, Stambaugh et al. 2007, Kabrick et al. 2015).

Conclusion

Our objective was to determine the effects of genetics, site preparation, and vegetation control on survival and growth of shortleaf pine seedlings. We found that competition remains the most significant barrier to survival and growth. While non-pedigree seedlings free from understory competition have similar survival and height growth to compared to pedigreed seedlings, they have significantly lower overall diameter growth. Genetic selection provided statistically significant gains in height and diameter growth, but the cost associated with this approach may be prohibitive for non-commercial applications. The use of non-pedigree stock, while minimizing understory competition during the first several growing seasons, should allow for successful shortleaf pine establishment under most site conditions encountered in Missouri.

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Chapter 5:

Assessing survival and growth potential of shortleaf pine (*Pinus echinata)* in the Missouri Ozarks through novel height growth percentiles

Stephen Lyczak

Abstract

Growth percentile charts are a common way to assess development of everything from human infants to livestock. We developed a tool for assessing early tree growth performance through height-growth percentile rankings and using those percentiles to predict future performance and survival probability for shortleaf pine in the Missouri Ozarks.

Over 5000 shortleaf pine seedlings across three sites were analyzed. Trees were assigned percentile classes: <25th, 50th, 75th, and >90th based on height one-year after planting (age 2 for 1-0 stock), and again after seven years. Of trees originally in the <25th percentile, 84% either maintained that percentile in year seven or died; while only 16% increased percentile. In the 50th percentile, 37% declined or died, 28% maintained their percentile, while 34% increased percentile. For the 75th percentile, 17% decreased significantly or died, 25% decreased marginally, while 57% sustained or increased percentile. Of trees in the >90th percentile, 51% maintained that percentile, 28% declined marginally, 20% declined significantly, while 0.9% died. Overall, most mortality and percentile declines occurred in the 50th percentile and below, while superior trees were more likely to survive and maintain their height class over time.

Introduction

In regenerating stands, there is a need at an early age to distinguish between trees that are likely to become canopy codominant or dominant trees from those that will not. Where shortleaf pine seedling are planted, the presence of woody and herbaceous competition can severely limit their growth and survival potential, reducing the probability of regeneration success, and reducing the efficacy of growth and yield tables, site index curves, and species growth curves (Sander and Rogers 1979, Lowery 1987, Dougherty and Lowery 1987, Guldin 2007). Though complex interactions in the early stages of stand development can cause differential growth patterns, many species can exhibit differentiation before other growth metrics become viable, and early growth can be a strong indicator of future performance (Assmann 1970, Oliver and Larson 1996).

Comparing the growth of individual trees to growth percentiles, in a similar manner to those used to assess the growth trajectory of children, is one way to assess the early growth of trees (Quetelet 1871, Vickers et al. 2014, Vickers et al. 2017). Identifying potentially low-vigor trees early can facilitate additional silvicultural treatments such as releases to ensure that they remain in the stand and continue to grow.

Height growth percentiles may also provide a good indication of survival probability. Survival probability is difficult to model, mainly due to the lack of data traceable to individual trees, or the inability to determine the factor(s) that contributed to mortality. However, individual trees that obtain a dominant canopy position tend to have higher survival than suppressed trees (Raley et al. 2003). As both growth and survival tend to be species-specific, large volumes of data are needed to create accurate models. Much of these data exist for commercially grown southern yellow pine species, where there is a financial incentive to track such information. In Missouri, there are several large datasets containing shortleaf pine growth from sites across the region.

Our objective is to quantify the height growth and survival of planted shortleaf pine seedlings. We employed height-growth percentiles and logistic regression modelling utilizing multi-location, multi-year datasets to calculate the height-growth percentiles and future growth potential and survival probabilities (to 7 years after planting) based on height percentile at year one, allowing managers and stakeholders to quickly estimate the ability of an individual tree to survive and grow much earlier than current tools allow.

Methods and Data Analyses

We used tree height and diameter growth data from three installations located in the Missouri Ozark Highlands. The first dataset was from the Long-Term Soil Productivity site (LTSP), Shannon County, MO (*N 37°10’48”, W 91°06’36”)*. Soils on site are primarily of the rocky, nutrient-poor Clarksville series (loamy-skeletal, siliceous, semi-active, mesic Typic Paleudults), formed from hillslope sediments and cherty residuum from dolomite, with a site index of 61 at age 50 for shortleaf pine (NRCS *Web Soil Survey* 2017). The study design is a 3x3, split-plot factorial to simulate harvest-related soil disturbances including, organic matter (biomass) removal, soil compaction, and vegetation control. The study was established in 1995, following an internationally implemented protocol (Powers 1990, Ponder and Mikkelson 1995). Tree height and diameter (basal diameter or diameter at breast height (DBH), depending on tree height) were collected annually from 1995 until 2004, with additional collections in 2013 and 2016. For additional information on study design, plot layout, and site characteristics, see Ponder and Mickelson (1995).

The second study was a shortleaf pine underplanting study at the Sinkin Experimental Forest, Reynolds and Dent Counties, MO (*N 37°29'24", W 91°15'36")*. Soils include the Clarksville and Coulstone series, both loamy-skeletal, siliceous, semi-active, mesic Typic Paleudults (site index 60 and 61, respectively, at age 50 for shortleaf pine), and the Nixa series, a loamy-skeletal, siliceous, active, mesic Glossic Fragiudults (site index 60 at age 50 for shortleaf pine)(NRCS *Web Soil Survey* 2017). The treatment included underplanting 1-0 bareroot shortleaf pine seedlings in an existing second-growth mixed hardwood stand after manipulating the overstory density from 0 to between 73% stocking. A severe storm one year after seedling planting removed additional overstory trees in some treatment plots, lowering the overstory density and residual basal areas per plot. In this study, the nearest hardwood competitor within 1.37 m to each planted shortleaf pine seedling was identified, tagged, and measured. These hardwood competitors were from either advance reproduction, or stump sprouts. This distance was selected because it corresponds to the growing space requirement of an 11-cm dbh hardwood tree as determined with published stocking equations (Gingrich 1967), thus representing the future growing space requirement of the hardwood competitors at about age 20, when the stand is undergoing the early stage of stem exclusion (Sander et al. 1984). The shortleaf pines were planted in

2007 and height and diameter (basal diameter or diameter at breast height, depending on height) were recorded annually in 2008 to 2010, and again in 2013 and 2017. Hardwood competitors were identified, tagged, and measured in 2010, 2013, and 2017. For additional information on study design, plot layout, and site characteristics, see Kabrick et al. (2011). The third study was established at the Wurdack Research Center, Crawford County, MO (*N 37°47'24", W 91°25'12").* The site is a continuous, south-facing slope of 10-30%, with two soil series occurring: Reuter, a loamy-skeletal, siliceous, active, mesic Typic Paleudalfs on the upper and lower backslopes (site index 61 at age 50 for shortleaf pine), and Goss, a clayey-skeletal, mixed, active, mesic Typic Paleudalfs occurring on lower slope positions (site index for shortleaf pine is 56 at age 50) (NRCS *Web Soil Survey* 2017). Seedlings consisted of genetically-improved, 1-0 containerized shortleaf pine stock representing 12 full-sib families, plus standard, orchard-run seedlings from the state nursey at Licking, MO. Families were crossed from elite parents selected in natural stands on the Mark Twain National Forest in the 1970s (Gwaze et al. 2005, Smith 2011). The existing hardwood forest was clearcut, and a masticator was used to grind tree stumps and non-merchantable material. The site was then divided into four blocks. Seedlings were deployed in complete blocks, with 700-1000 seedlings per block. Three blocks had a silvopasture treatment applied, which involved a double row of trees spaced 3.05m x 3.05m followed by a 12.19m wide alley. A mix of native warm and cool season grasses were broadcast seeded into the alleyways. Herbicide pellets (Velpar®) were applied to the seedling planting rows for two years following planting. The fourth block eliminated the alley, leaving rows evenly spaced at 3.05 meters. No herbicides were applied in this block and no grasses were seeded.

Instead, an additional 12 families (not replicated in the other three blocks) were selected and planted along with the 12 replicated families. Pine height and diameter (basal diameter or diameter at breast height, depending on height) were collected in 2010, 2011, and 2017. For additional information on study design, layout, site characteristics, and genetic selection, see Lyczak (2019).

Data Analysis

Height percentile was based upon the height and age of each tree, independent of site. Percentiles were obtained from individual tree heights using the PROC UNIVARIATE procedure in SAS Version 9.4 (SAS Institute, Cary, NC). To ensure proper calculation of percentiles, growth years were analyzed individually. Only live trees were used, including stump sprouts from previously top-killed individuals. Corresponding percentiles were added to the respective master data files for each tree individually.

To determine the probability of trees moving between percentiles through time, calculated percentiles (1^{st} through 99^{th}) were reduced to four percentile classes based on confidence intervals: ≤25^{th} percentile, 50^{th} percentile, 75^{th} percentile, and ≥90^{th} percentile. Probability of an individual tree's percentile class change from year 1 to year 7, including survival probabilities, were estimated using the PROC LOGISTIC procedure in SAS Version 9.4 (SAS Institute, Cary, NC). Survival probability analysis included percentile classes, as well as height (cm), basal diameter (mm), and the associated interactions.

Results

Shortleaf pine height-growth percentiles from planting through year 21 are presented in Figure 1. Wide separation between percentile classes from the 1st through the 25th is notable. Separation is more uniform at the 50th percentile and above. After 21 years, trees in the lowest percentile are approximately 5.0m tall; while trees in the highest are approximately 16.0m tall. The average (50th percentile) shortleaf pine is approximately 13.0m tall twenty-one years after planting. While separation at the bottom percentiles is more easily identifiable, all percentiles are clearly divergent around 5 years after planting.

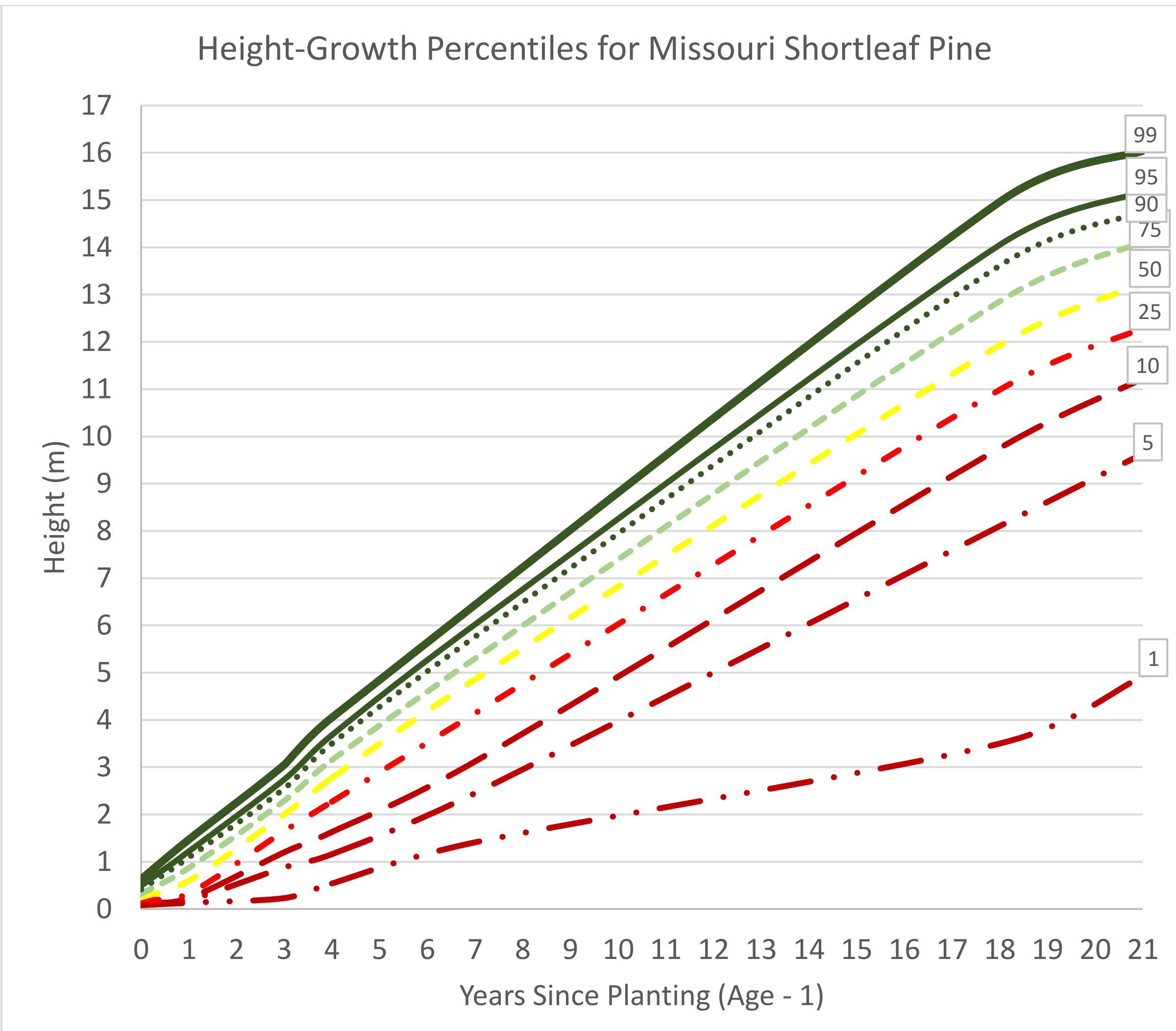

Figure 10. Complete height-growth percentiles for shortleaf pine in Missouri from planting through 21 years.

Simplified and condensed percentile curves from planting though year 10 are presented in Figure 2. These curves, based on the confidence intervals from the percentiles in Figure 1, show marked and widening separation between percentiles classes as early as 2 years after planting. By year 10, there is 1.0m difference between the 25th and 50th percentiles, and over 2.5m difference between the ≤25th and the ≥90th percentiles.

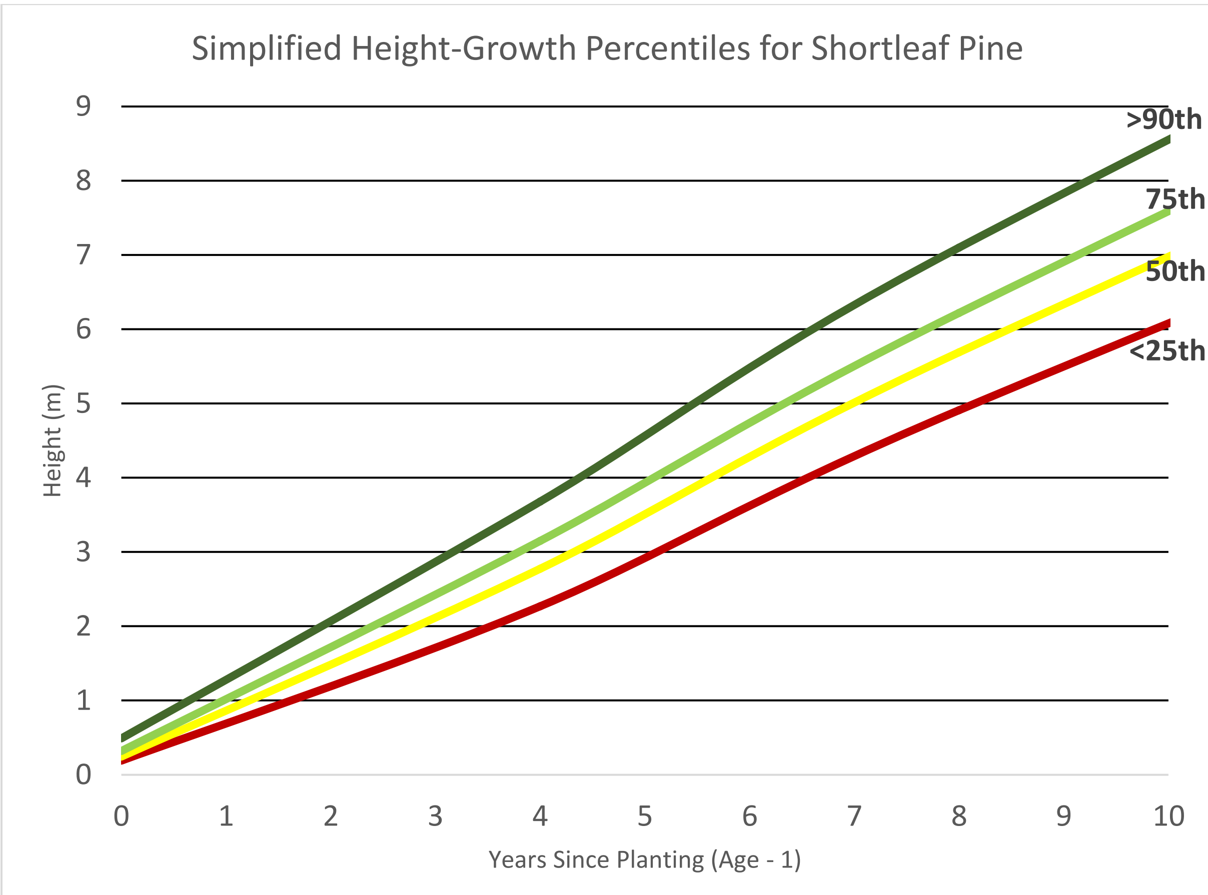

Figure 11. Simplified and truncated height-growth curves for Missouri shortleaf pine. Confidence intervals from the 1st, 5th, 10th, and 25th percentiles were used to delineate the <25th percentile class; the confidence intervals for the 90th, 95th, and 99th percentiles were used to create the >90th percentile class. The 50th and 75th remain as in Figure 1.

Probabilities of individuals changing percentile class from 1 year after planting to 7 years after planting are summarized in Figure 3. For trees in the ≤25th percentile, probability of mortality 7 years after planting was approximately 0.47, while the probability of moving into the 75th or >90th percentile was less than 0.05. Conversely, trees that began in the

≥90th percentile were more likely (0.77 probability) of being in the 75th or above percentile after year 7, and less likely (0.05 probability) of being in the ≤25th percentile. The 50th percentile was more balanced, with a 0.54 probability of a tree maintaining or improving percentile class, and a 0.46 probability of declining or dying after 7 years.

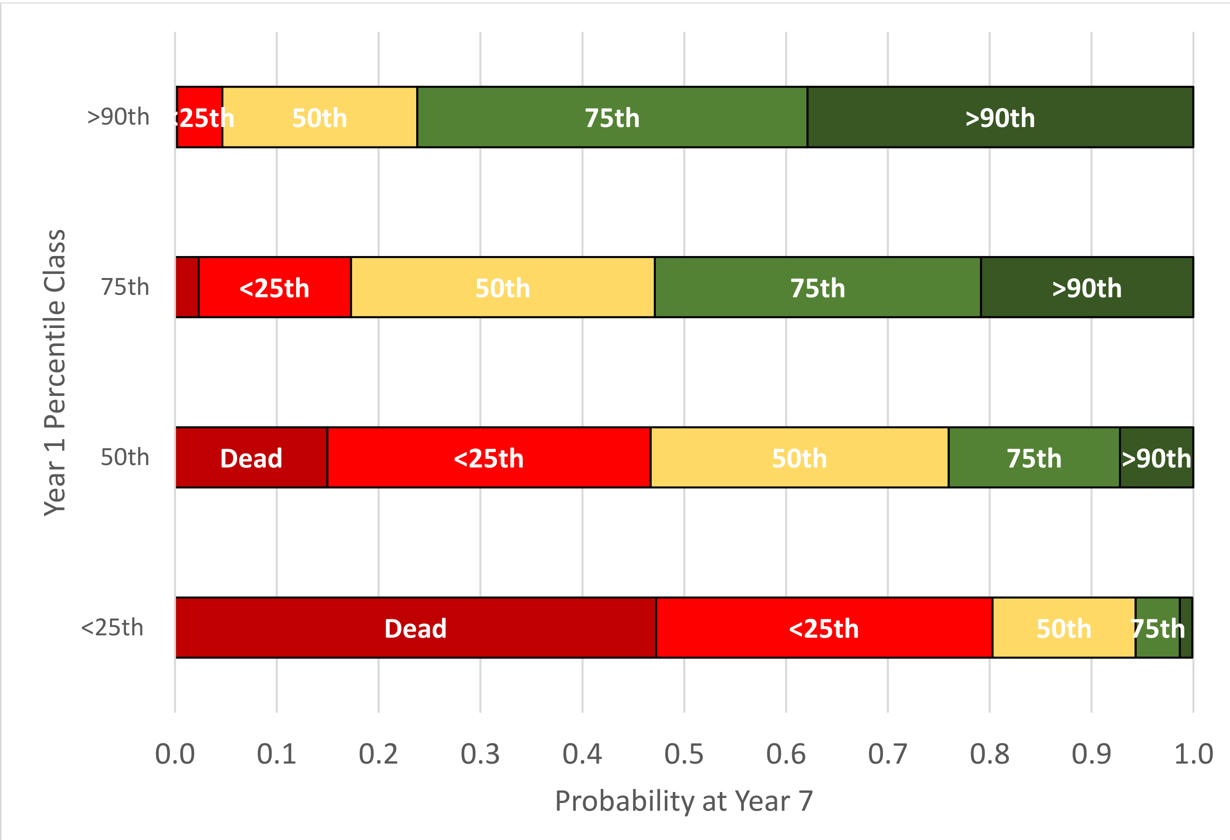

Figure 12. Probability predictions of tree status (percentile class: <25th, 50th, 75th, >90th) seven-years after planting based on percentile class (<25th, 50th, 75th, >90th) at one-year after planting. "Dead" indicates probability of tree mortality, while numbers represent percentile class. All probabilities sum to 1.0. Probability estimates for lower percentile classes show a greater propensity of remaining in a lower percentile class (or dying), while those trees in higher percentile classes initially are more likely to maintain or increase their percentile class 7 years after planting.

Survival probability was modeled using several tree-specific variables (Table 1). Single-variable models (i.e. percentile class only, height only, and/or diameter only) resulted in R^2 values between 0.70 and 0.72, and Akaike Information Criterion (AIC) scores between 3129 and 3256. Absolute height had the highest R^2 at 0.72, and lowest AIC at 3129. The addition of diameter to either percentile class or height increased R^2 to 0.73, and reduced AIC to

3028 and 3010 for percentile class and height, respectively. The full model, which includes percentile class, diameter, and the percentile class x diameter interaction, resulted in R^2 values of 0.75 for both models, but a significantly lower AIC score for the model utilizing percentile (2830) versus actual height (2858).

Table 1. Year 7 survival probability model parameters (standard error) for planted 1-0 shortleaf pine seedlings.

Model	β_0 Intercept	β_1 Height percentile	β_2 Diameter	β_3 Height	β_4 Interaction	AIC	R^2
Height percentile (P)	-2.77 (0.089)	2.48 (0.071)				3227	0.70
Diameter (D)	-2.19 (0.070)		0.38 (0.011)			3256	0.70
Height (H)	-2.74 (0.087)			0.090 (0.003)		3129	0.72
P + D	-2.76 (0.090)	1.46 (0.099)	0.184 (0.015)			3028	0.73
H + D	-2.72 (0.088)		0.152 (0.016)	0.060 (0.004)		3010	0.73
P + D + (PxD)	**-3.73 (0.134)**	**2.17 (0.116)**	**0.370 (0.022)**		**-0.103 (0.006)**	**2830**	**0.75**
H + D + (HxD)	-3.38 (0.113)		0.280 (0.018)	0.080 (0.004)	-0.003 (0.001)	2858	0.75

Model form is $Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots \beta_n X_n$, where *Y* is shortleaf pine survival probability seven years after planting, β_0 is the intercept, and β_n are the parameters for individual tree variables: X_1 is percentile class (≤25th, 50th, 75th, ≥90th) at year one, X_2 is basal diameter at year one (in mm), X_3 is height at year one (in cm), and X_4 is the interaction of i) percentile class x diameter, or ii) height x diameter (as indicated above). AIC represents Akaike Information Criterion score, and R^2 is the maximum scaled coefficient of determination. All models are significant ($p<0.001$), while the model in bold has the most support based upon AIC and R^2 criteria.

Discussion

Shortleaf pine height-growth percentiles provide important information about their growth potential under a wide variety of stand and site conditions. By pooling data from edaphically similar sites that employ diverse treatments ranging from understory vegetation control to genetic improvement, a reasonable range of shortleaf pine growth is represented. The primary advantage to utilizing height percentiles in lieu of mean heights are the statistical benefits of a distribution (Vickers et al. 2017). Tree height growth data have large variances, which can needlessly complicate analyses, and more importantly, model fit. By eliminating much of this variance, and creating a growth chart specific to shortleaf pine, managers can quickly assess the status of individual trees.

Existing tools can accurately assess growth potential of mature shortleaf pine stands, estimating merchantable yields under set growing conditions (Murphy and Beltz 1981, Murphy and Farrar 1985, Murphy 1987). However, many of these growth and yield models were developed for uneven-aged stands containing merchantable trees that are far beyond the stand initiation phase of development. Consequently, these models do not incorporate the effects of over- and understory competition that are so important during the understory initiation and early stem exclusion stages of stand development. Employing an individual height percentile to predict survival probability prior to or during the early stem exclusion stage provides a valuable tool for assessing regeneration potential of individual shortleaf pine seedlings. The relationships between tree growth and site factors are unique, and they can inform stand improvement activities, thinning, and other silvicultural practices designed to encourage the growth of shortleaf pine in early stand development stages (Brinkman and Rodgers 1967, Assmann 1970, Oliver and Larson 1996).

The height-growth percentiles resemble the more traditionally used site index curves. While site index is well known by practicing foresters and provides a common frame of reference that is well understood, it does not provide a good metric for evaluating young trees due to the assumptions used for its determination. Site index values are derived from trees that have good form and judged to have been free-to-grow (Nash 1963), which is not the case for most of the trees during stand initiation. Site index also, by definition, is an assessment of the site quality—which is intended to exclude other confounding effects including light availability, interspecific competition, and genetic expression, that are used to derive height growth percentiles. Also, site index curves traditionally apply to stands that are age 10 or older. This age corresponds to the period after canopy closure of the regenerating cohort has occurred, and long after there are opportunities to affect species composition through thinning or release. With height growth percentile curves, regenerating trees can be assessed as early as age 1 when there is still ample time to change the course of stand development.

Predictive models all show a strong relationship between survival probability and height (actual height and percentile class) and basal diameter. While all models tested were significant ($p<0.001$) with R^2 values >0.70, the most complex model that included height or percentile class by basal diameter interactions had both the lowest AIC scores (<2858) and highest R^2 (≥0.75). These significant interactions indicate that for given diameter, shorter seedlings had greater survival, a result that we attribute to a greater root to shoot ratio. However, single-variable models had only slightly greater AIC scores and slightly lower R^2 values than those with interaction terms. Of the single-variable models, the one that included the actual height performed slightly better (AIC = 3129, R^2 = 0.72) than those with height percentile class or actual diameter. This suggests that height percentile class does not offer a better fit than actual height or diameter for predicting survival rate. However, all three single-variable models performed well, suggesting that each of the three variables provide similar estimates. Future research should test these relationships further by comparing predictions made with these models with an independent data set.

Shortleaf pine restoration remains a focus in Missouri (Barnett et al. 1987, Gwaze et al. 2006, Jensen et al. 2007, Jensen and Gwaze 2007, Kabrick et al. 2015). The oak-pine forest type most commonly found in Missouri supports a diverse array of mammals, birds, and insects not typically found when pine is absent (Lawson 1990, Masters 2007). Diverse landscapes have increased resilience to everything from climate change to insect outbreaks (Hanberry et al. 2015). Successful restoration of shortleaf pine requires that seedlings are able to establish and grow under the array of conditions found in the forests of south and southeastern Missouri, and the difficulties of establishing this species along with oaks and other hardwoods has shown to be difficult (Kabrick et al. 2015). These height-growth percentiles, and their associated growth potential probabilities are a simple way to assess the success of restoration efforts, while providing an opportunity early in the restoration process to take corrective action.

Conclusion

Height growth percentile curves have the potential to fill the knowledge gaps in early tree development. For most tree species, the first 10 years of growth are highly variable, and more dependent upon site factors, resource availability, and competition than after recruitment into the overstory. Height growth percentiles minimize much of the inherent variance found in height-age data and can consolidate and categorize a continuous variable (height) into a discrete variable (percentile) easing the process by which various relationships can be identified and analyzed. The efficacy of height growth percentiles, coupled with the apparent relationship between tree height and survival could provide a valuable predictive tool for researchers, foresters, and forest landowners, for assessing shortleaf pine regeneration potential. Height growth percentiles are easy to use and require only simple tree measurements. Based on the best available data from several long-term sites in the Missouri Ozark Highlands, those predicted results are consistent with actual observations in real timber stands, further enhancing the utility of this model. Though these models currently apply to a limited number of species in a specific region, the potential to develop more wide-ranging and encompassing models is evident, and obvious. We hope scientists in other regions will attempt to develop similar predictive models and improve upon the processes presented here.

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Chapter 6:

Effects of competitive interactions on the survival, height, and diameter growth of artificially regenerated shortleaf pine in artificial and naturally regenerated mixed hardwood stands in the Missouri Ozarks

Stephen Lyczak

Abstract

There is renewed interest in restoring shortleaf pine in pine-oak forests to increase resiliency and heterogeneity. Establishing shortleaf pine across portions of its historical range has proven challenging due to shade intolerance, slow early growth, and poor competitive ability. Our objective was to determine the expected survival and growth rates of planted shortleaf pine relative to artificial and natural hardwoods and to identify barriers to restoration success. We used data from three long-term studies in southeastern Missouri to examine the survival and growth of over 5500, 1-0 seedlings as a function of understory competition and overstory density in artificially and naturally regenerated stands. Growth of planted 1-0 shortleaf pine exceeded that of planted 1-0 white oak (*Quercus alba)* and northern red oak (*Q. rubra*) when grown in the open during a 22-year monitoring period. However, during the first 10 years, planted shortleaf pine had lower survival and height growth where competing with natural oaks and other hardwood regeneration originating from advance reproduction rather than planted seedlings. Regression analysis indicated that height and diameter growth in natural stands was further reduced by retaining a hardwood overstory, while survival was not. Planted shortleaf pine grows faster than planted oaks in open stands with few other hardwood competitors. However, most restorations occur in mixed hardwood stands where large advance reproduction outcompetes planted shortleaf pine after harvesting. Although retaining a partial overstory reduces height and diameter growth, data show the importance of controlling understory competitors.

Introduction

Shortleaf pine has the widest distribution of any southern pine in the United States. Its range includes portions of 22 states from New York and New Jersey in the northeast to Texas and Oklahoma in the south-central part of the country, an area encompassing over 1.1 million km^2 (Lawson 1990). Shortleaf pine is the only pine species native to Missouri, where it once covered over 2.5 million hectares in the south, and southeastern parts of the state (Liming 1946). Shortleaf pine could historically be found growing among oaks (*Quercus* spp.), hickories (*Carya* spp.), and other, mainly upland, hardwood species. It could occur as a species of varying importance—from only several trees per hectare to 50% or more of the composition in a stand (Brinkman and Rogers 1967). From the late 1800s through the 1920s, extensive harvesting of shortleaf pine took place in Missouri, reducing the abundance of this species to some 15-50% of pre-exploitation numbers (Cunningham 2007, Guyette et al. 2007).

Restoration of shortleaf pine throughout Missouri is an ongoing area of concern (Barnett et al. 1987, Kabrick et al. 2007). While the outcome of any restoration effort can be unpredictable (see Grman et al. 2013), there are many benefits to restoring shortleaf pine ecosystems. Mixed oak-pine systems support an array of mammals, birds, insects, and herpetofauna that do not occur when a pine component is missing from the landscape (Lawson 1990, Eddleman et al. 2007, Masters 2007). Diverse ecosystems have been shown to be more resilient than novel or altered ecosystems, providing a buffer to the effects of climate change, altered disturbance regimes, and invasion by exotic species and pathogens (Hobbs et al. 2006, Funk et al. 2008, Hanberry et al. 2015, Kabrick et al. 2017). Shortleaf pine restoration efforts within Missouri have focused primarily on artificial regeneration through planting bareroot or containerized shortleaf pine seedlings. Though all restored ecosystems are supported or perpetuated to some extent by human actions (Hobbs et al. 2011), one of the goals of restoration should be a system that has the ability to persist with a minimal amount of intervention (Montalvo et al. 1997). Therefore, restoration of oak-pine forests in Missouri should focus on the establishment of shortleaf pine seedlings within a stand, the rapid growth and recruitment of those seedlings, and the natural regeneration required to maintain the presence of shortleaf pine in the stand. The challenges facing restoration efforts can include competition from woody and herbaceous vegetation in the understory, lack of genetic diversity, and altered disturbance regimes (Dougherty and Lowery 1987, Lowery 1987, Lawson 1990, Gwaze et al. 2007, Broadhurst et al. 2008).

To examine these barriers more closely, we analyzed three shortleaf pine plantings in Missouri: 1) shortleaf pine underplanting in an existing hardwood forest, where Gingrich (1967) stocking levels varied from 0% to 74%, 2) shortleaf pine planting that employed genetically selected trees and vegetation control, and 3) oak-pine planting where 1-0 northern red and white oak seedlings were planted with 1-0 shortleaf pine seedlings in split-plots with half including vegetation control, and half without. Our objectives are to determine how these various treatments and restoration regimes impact the survival, height growth, and diameter growth of shortleaf pine seedlings and hardwood species either planted or identified as advance reproduction/stump sprouts, at various stages of stand development, while concentrating on the period prior to canopy closure (approximately age 10).

Methods

Data for the shortleaf pine underplanting study was from a study conducted at the *Sinkin Experimental Forest*, Reynolds and Dent Counties, MO (*N 37°29'24", W 91°15'36")*. Soils include the Clarksville and Coulstone series, both loamy-skeletal, siliceous, semi-active, mesic Typic Paleudults, as well as the Nixa series, a loamy-skeletal, siliceous, active, mesic Glossic Fragiudults (NRCS *Web Soil Survey* 2017). Data for the genetic selection pine planting study was from the Wurdack Research Center in Crawford County, MO (*N 37°47'23.9", W 91°25'12").* The site is a continuous, south-facing slope of 10-30%, with two soil series occurring: Reuter, a loamy-skeletal, siliceous, active, mesic Typic Paleudalfs on the upper and lower backslopes, and Goss, a clayey-skeletal, mixed, active, mesic Typic Paleudalfs occurring on lower slope positions (NRCS *Web Soil Survey* 2017). Data from the oak-pine planting was from the *Long-Term Soil Productivity site* (LTSP), Shannon County, MO (*N 37°10'47.9", W 91°6'35.9")*. Soils on site are primarily of the rocky, nutrient-poor Clarksville series (loamy-skeletal, siliceous, semi-active, mesic Typic Paleudults), formed from hillslope sediments and cherty residuum from dolomite (NRCS *Web Soil Survey* 2017). At all three sites, the site index (base age 50) for shortleaf pine was 18.3 m for most mapped soil series, while one series (Goss at Wurdack) was 17.1 m (California Soil Resource Lab *SoilWeb* 2017). Thus, height and diameter growth differences among the three sites were likely due to treatments rather than site factors.

At the Sinkin Experimental Forest, treatments included underplanting 1-0 bareroot shortleaf pine seedlings in an existing second-growth mixed hardwood stand after manipulating the overstory stocking levels to between 0-73%, and a 100% control. A windstorm one year after seedling planting removed additional overstory trees in some treatment plots, lowering the overstory density and residual basal areas per plot. To determine the effects of competition on shortleaf pine seedlings, the nearest hardwood competitor (from either advance reproduction or stump sprouts) within 1.37 m to each planted shortleaf pine seedling was identified, tagged, and measured. These hardwood competitors were from either advance reproduction, or stump sprouts. This distance was selected because it corresponds to the growing space requirement of a canopy dominant or codominant 11-cm dbh oak tree in regenerating stands at approximately age 20 during the early stage of stem exclusion, thus representing the future growing space requirement of the hardwood competitors (Sander et al. 1984). The shortleaf pines were planted in 2008 and height and diameter (basal diameter or diameter at breast height, depending on height) were recorded annually in 2008 to 2010, and again in 2013 and 2017. Hardwood competitors were identified, tagged, and measured in 2010, 2013, and 2017. For additional information on study design, plot layout, and site characteristics, see Kabrick et al. (2011).

At Wurdack, seedlings consisted of genetically-improved, 1-0 shortleaf pine containerized stock representing 12 full-sib families, plus standard, orchard-run seedlings from the state nursey at Licking, MO. Families were crossed from elite parents selected in natural stands on the Mark Twain National Forest in the 1970s (Gwaze et al. 2005, Smith 2011). The existing hardwood forest was clearcut, and a masticator was used to grind tree stumps and non-merchantable material. The site was then divided into four blocks. Seedlings were deployed in complete blocks, with 700-1000 seedlings per block. Three blocks had a silvopasture treatment applied, which involved a double row of trees spaced 3.05m x 3.05m followed by a 12.19m wide alley. A mix of native warm and cool season grasses were broadcast seeded into the alleyways. Herbicide pellets (Velpar®) were applied to the seedling planting rows for two years following planting. The fourth block eliminated the alley, leaving rows evenly spaced at 3.05 meters. No herbicides were applied in this block and no grasses were seeded. Instead, an additional 12 families (not replicated in the other three blocks) were selected and planted along with the 12 replicated families. Tree heights and diameters were measured in 2010, 2011, and 2017.

At the LTSP, a 3x3, split-plot factorial study design, to simulate harvest-related soil disturbances, and consisting of organic matter (biomass) removal, soil compaction, and vegetation control was established in 1995, following a nationally-implemented protocol which dictated methodology (Powers et al. 1990, Ponder and Mikkelson 1995). Three levels of organic matter removal included: removal from site of tree boles only, whole tree (bole, top, limbs), and whole tree plus forest floor (tree bole, top, limbs, and raking of forest floor to remove the organic soil horizon). Three levels of soil ("whole-soil") compaction were implemented: no compaction (average whole-soil density of ~1.30 g/cm^3), moderate compaction (average whole-soil density ~1.60 g/cm^3), and severe compaction (average whole-soil density ~1.80 g/cm^3). In addition, half of each treatment plot had chemical herbicide applied annually for 10 years following seedling planting. Bare-root, 1-0 northern red oak, white oak, and shortleaf pine were planted following the application of the treatments (only shortleaf pine data are included in these analyses). Tree height and diameter (basal diameter or diameter at breast height, depending on tree height) were collected annually from 1995 until 2004, with additional collections in 2013 and 2016. For additional information on study design, plot layout, and site characteristics, see Ponder and Mickelson (1995) and Lyczak (2019a).

Data Analysis

Survival probabilities for each assessment event were determined using logistic regression analyzed separately by site. We used a generalized linear mixed model with a binary distribution (survival =1, mortality =0), logit link function, and random intercept using PROC GLIMMIX in SAS 9.4 software (SAS Institute, Inc., Cary, NC). Treatment effects on tree heights and diameters were analyzed using a generalized linear mixed model with a gamma distribution and log link function using PROC GLIMMIX in SAS 9.4 software (SAS Institute, Inc., Cary, NC). We used linear regression, separated by site, to identify relationships between treatments (overstory density, vegetation control, and genetic selection, as applicable) and tree height and diameter. Sinkin shortleaf pine and hardwood competitor height and diameter were obtained using the ESTIMATE function in GLIMMIX for each overstory stocking level. Least-square means of tree heights were subjected to pairwise comparisons using T-grouping at *alpha*=0.05.

Results

Survival

Survival probability was highly variable by treatment and site (Figure 1). Survival for underplanted shortleaf pine seedlings was not significantly affected by stocking level ($p>0.100$), except in year 3, where it was marginally significant ($p=0.033$) (Figure 1a). Survival probability declined from 70% in year 2, to 45% in year 6, to only 25% in year ten.

In the genetic selection pine planting, survival probability was significantly affected by both genetic selection and understory vegetation control (VC) ($p<0.001$) (Figure 1b). Genetically selected seedlings with VC had a survival of >90% all 8 years, while non-genetic seedlings with VC had an 83% probability of survival. Seedlings with no VC had a survival probability of 79% in year 1, dropping to 71% after 8 years. For the oak-pine planting, VC was not significant for shortleaf pine throughout the study duration ($p>0.202$). Survival probability for planted shortleaf pine averaged 60% from planting through year 6, after which it remained near 50%, regardless of treatment (Figure 1c). For northern red and white oaks, VC was not significant from planting through 9 years after planting ($p>0.269$). However, VC significantly affected survival probability starting 9 years after planting ($p<0.001$). Survival probabilities for both oaks with VC were ≥80% through year twenty-one. After year 9, survival probability for northern red oak with no VC drops from 80% to 35%, while white oak declines from 80% in year 9 to 65% in year twenty-one.

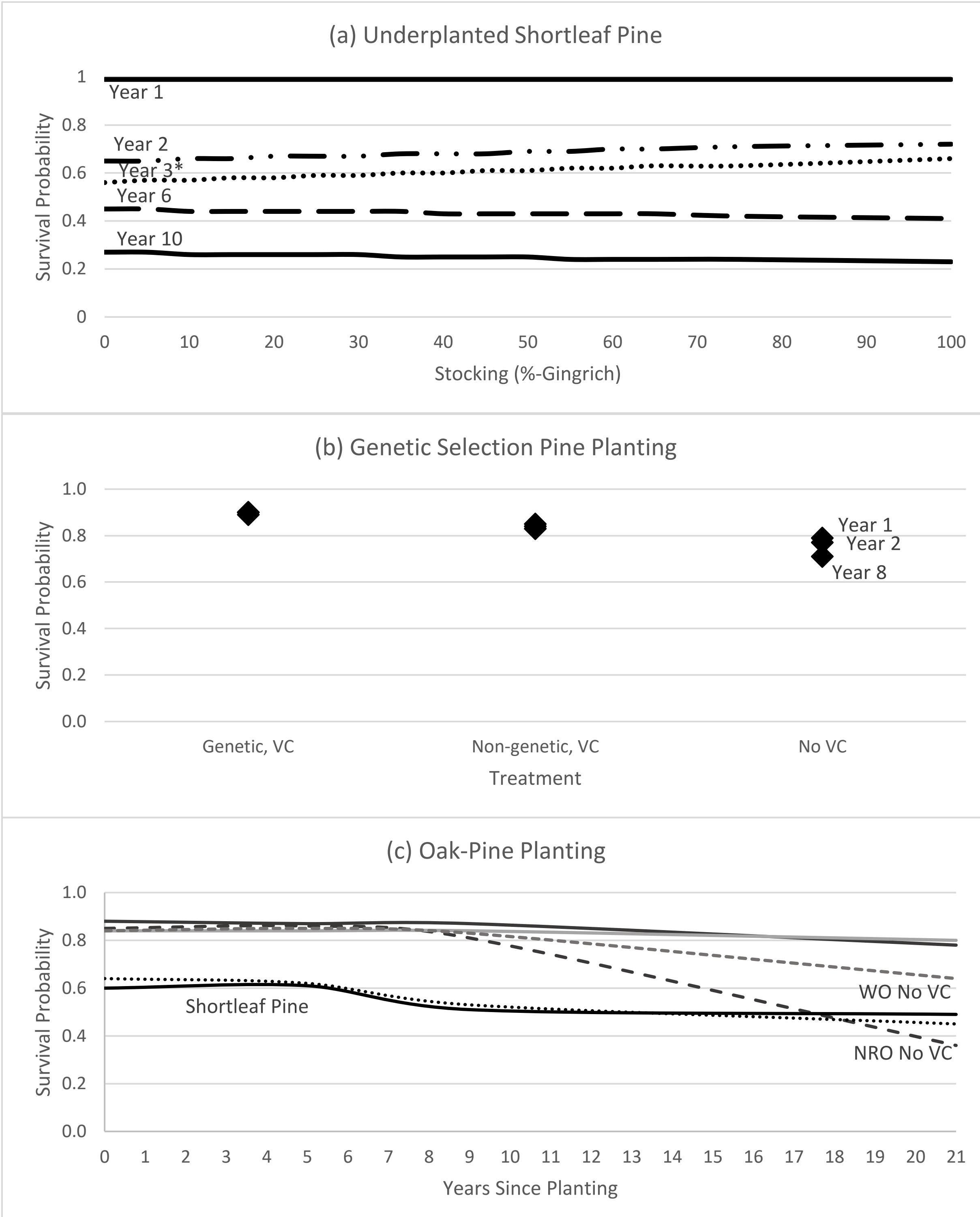

Figure 13. Survival probability by site/treatment. a) Underplanted seedling: survival probability by overstory stocking. Only in year 3 was stocking significant. b) Genetic selection pine planting: survival probability by genetic selection and VC treatment. In all measured years, genetics and VC were significant. c) Oak-pine planting: species-specific survival by VC treatment (solid line=VC, dashed line=no VC). Shortleaf pine survival was not affected by VC, nor were northern red and white oaks until year 9. Starting year 10, VC was a significant factor in survival of both oaks. Northern red and white oaks in the VC treatment are not labeled due to their nearly identical survival probabilities.

Height Growth

Overstory stocking did not significantly reduce shortleaf pine growth during the first two years following planting (p>0.061). However, starting 3 years after planting, shortleaf pine heights decreased significantly (p<0.001) with increasing overstory density (Figure 2a). Hardwood growth from advanced reproduction/stump sprouts was significantly reduced (p<0.001) by increasing overstory stocking at all three measurements (Figure 2b).

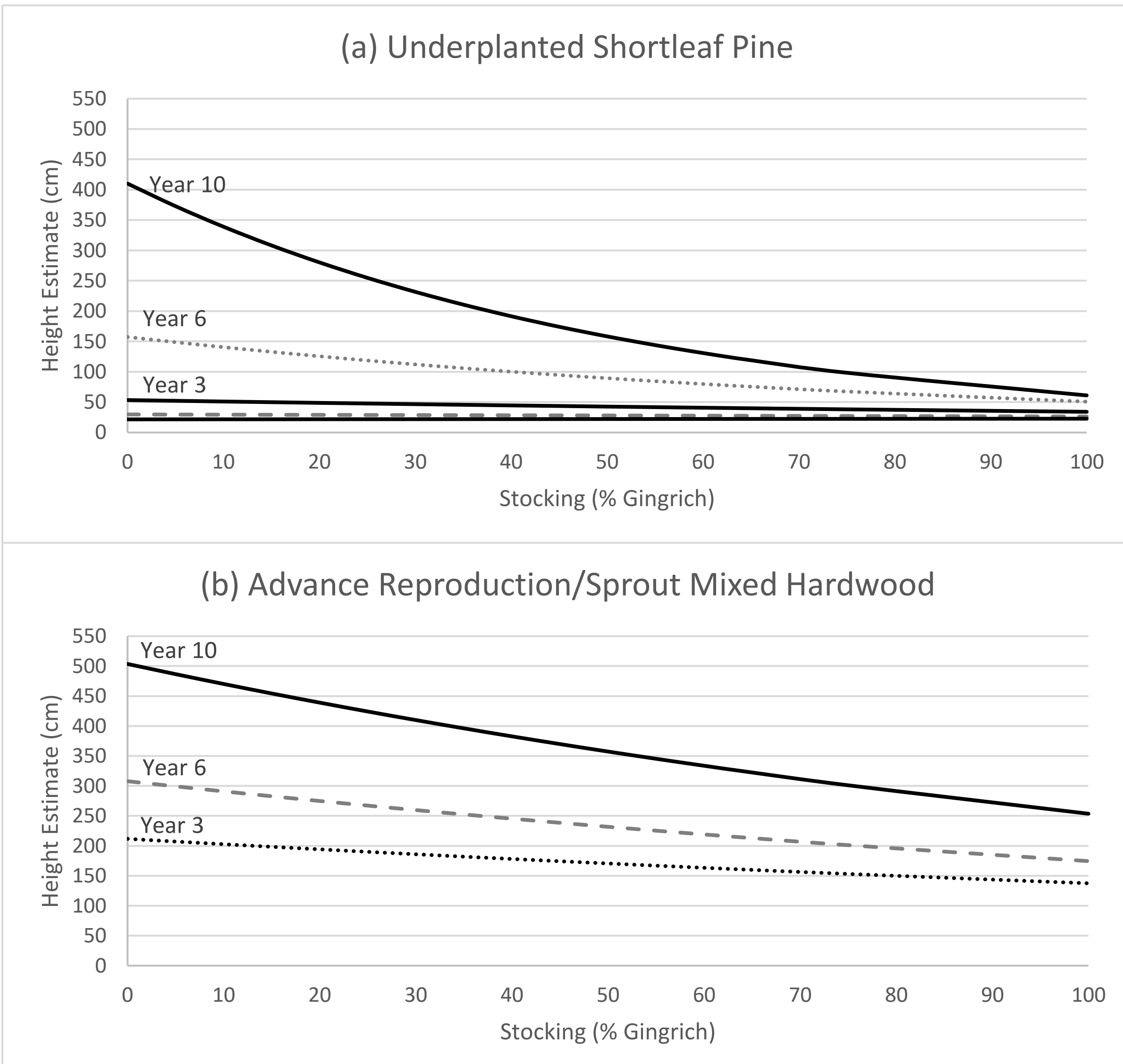

Figure 14. Height estimates for (a) underplanted shortleaf pine and (b) advance reproduction/sprouted mixed hardwoods by Gingrich stocking level. Increasing overstory density significantly decreased height growth starting in year 3 for shortleaf pine and the hardwoods. The effect of increasing overstory stocking is more pronounced in shortleaf pine than hardwoods, based on the slope of the respective curves.

the shortleaf pines (300cm vs 152cm in clearcuts). In year 10, the hardwoods averaged 500cm in clearcut treatments, while the shortleaf pine averaged 400cm. Growth rates of advanced reproduction/stump sprout hardwoods are similar to those of planted shortleaf pine through time, though the hardwoods remain taller overall (Figure 3).

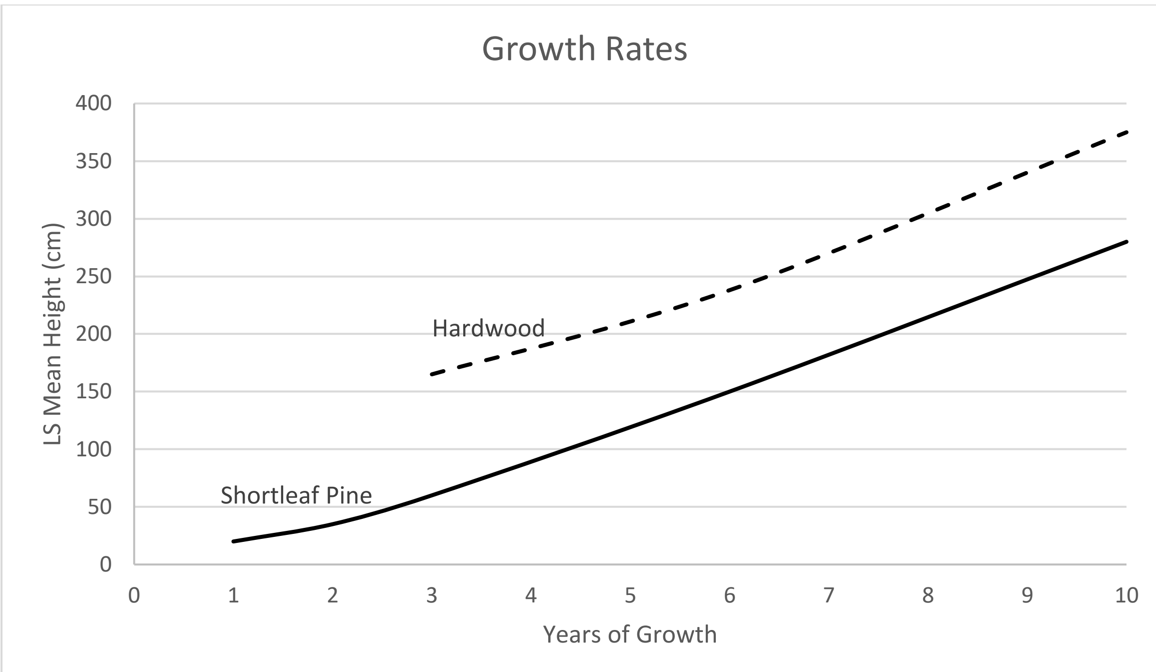

Figure 15. Growth rates of underplanted shortleaf pine and advance reproduction/stump sprout hardwoods, irrespective of treatment. Hardwood heights were not collected until year 3 of the study, while shortleaf pine heights were collected from inception. Planted shortleaf pine exhibit nearly identical growth rates to the hardwood species, though the hardwoods begin and remain taller overall.

Shortleaf pine heights through 8 years were significantly increased by both genetic selection and vegetation control ($p<0.001$) in the genetic selection pine planting (Figure 4). Eighth-year heights without VC were 319cm; applying VC increased mean height to 377cm, while the combination of genetic selection and VC resulted in a mean height of 429cm, increases of 18% and 35%, respectively. In the oak-pine planting, VC was significant for shortleaf pine, northern red oak, and white oak ($p<0.001$) after 22 years (Figure 5). The 10-year heights for northern red and white oak are comparable to advance reproduction/stump sprouts in Figures 2a and 2b, averaging 478cm for northern red oak and 433cm for white oak with VC; while no VC means were 372cm and 273cm for northern red and white oak, respectively.

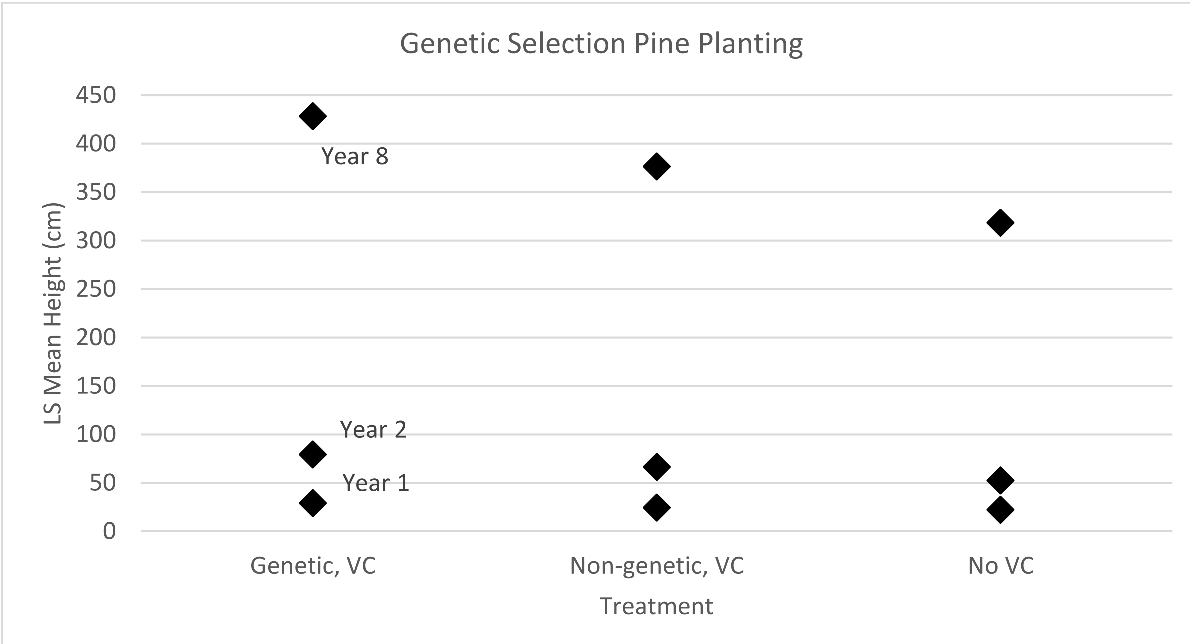

Figure 16. Least-square mean heights for shortleaf pine in a genetic selection planting, by genetic and vegetation control (VC) treatment. Genetic treatment and VC treatment are significant (p<0.001) for all years. At year 8, seedlings with no VC had a mean height of 319cm. Adding VC treatment to non-genetic trees increased mean height to 377cm, while further adding genetic selection resulted in a mean height of 429cm.

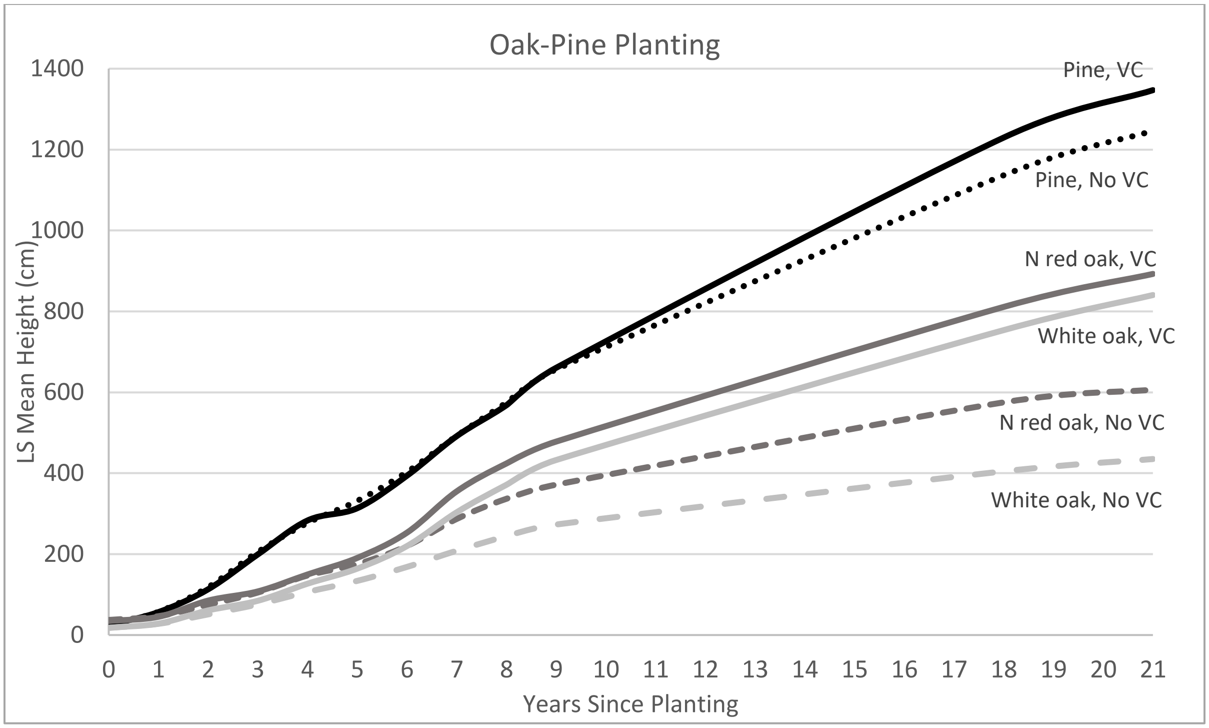

Figure 17. Least-square mean heights for planted shortleaf pine, northern red oak, and white oak through 21 years (age 22) by VC treatment. Solid lines represent results in VC treatment; dashed lines are no VC treatment for each species. VC significantly reduced height growth for all 3 species ($p<0.001$), though that reduction was more severe in the oaks.

Diameter Growth

Stocking level was not a significant effect for diameter growth during the first 2 years for shortleaf pine ($p>0.184$). From year 3 through 10, increasing stocking significantly reduced ($p<0.001$) basal diameter growth (Figure 6a). In advance reproduction/stump sprout hardwoods, increased stocking level significantly reduced ($p<0.001$) diameter growth in all measurement years, though to a lesser degree than shortleaf pine (Figure 6b). Both shortleaf pine and hardwood trees in 0% stocking (clearcuts) had the highest estimated basal diameter at 63mm. As stocking increased, shortleaf pine diameters declined, falling to 26mm at 50% stocking, and only 10mm at 100%. Hardwood species also had reduced diameter growth. At 50% stocking, the mean hardwood basal diameter was 44mm, falling to 33mm at 100% stocking. In the genetic selection pine planting, both genetics and VC significantly increased ($p<0.001$) diameters in all measurement years (Figure 7). Year 1 diameters between treatments were similar, ranging from 8mm in the no VC treatment to 9mm in the genetic VC treatment. By year 8, the mean no VC diameter (DBH) was 59mm, the addition of VC resulted in a mean diameter of 73mm, while genetic selection and VC had a mean diameter of 87mm. In the oak-pine planting, vegetation control significantly increased ($p<0.001$) diameter growth for shortleaf pine, northern red oak, and white oaks throughout 21 growing seasons (Figure 8). Shortleaf pines had drastically greater mean diameters after 21 years, averaging 282mm with VC, and 203mm with no VC. This compares to 109mm with VC for white oak, and 102mm with VC for northern red oak. In no VC treatments, northern red and white oak diameter was reduced by over half through 21 years, averaging only 47mm and 37mm after 21 growing seasons, respectively.

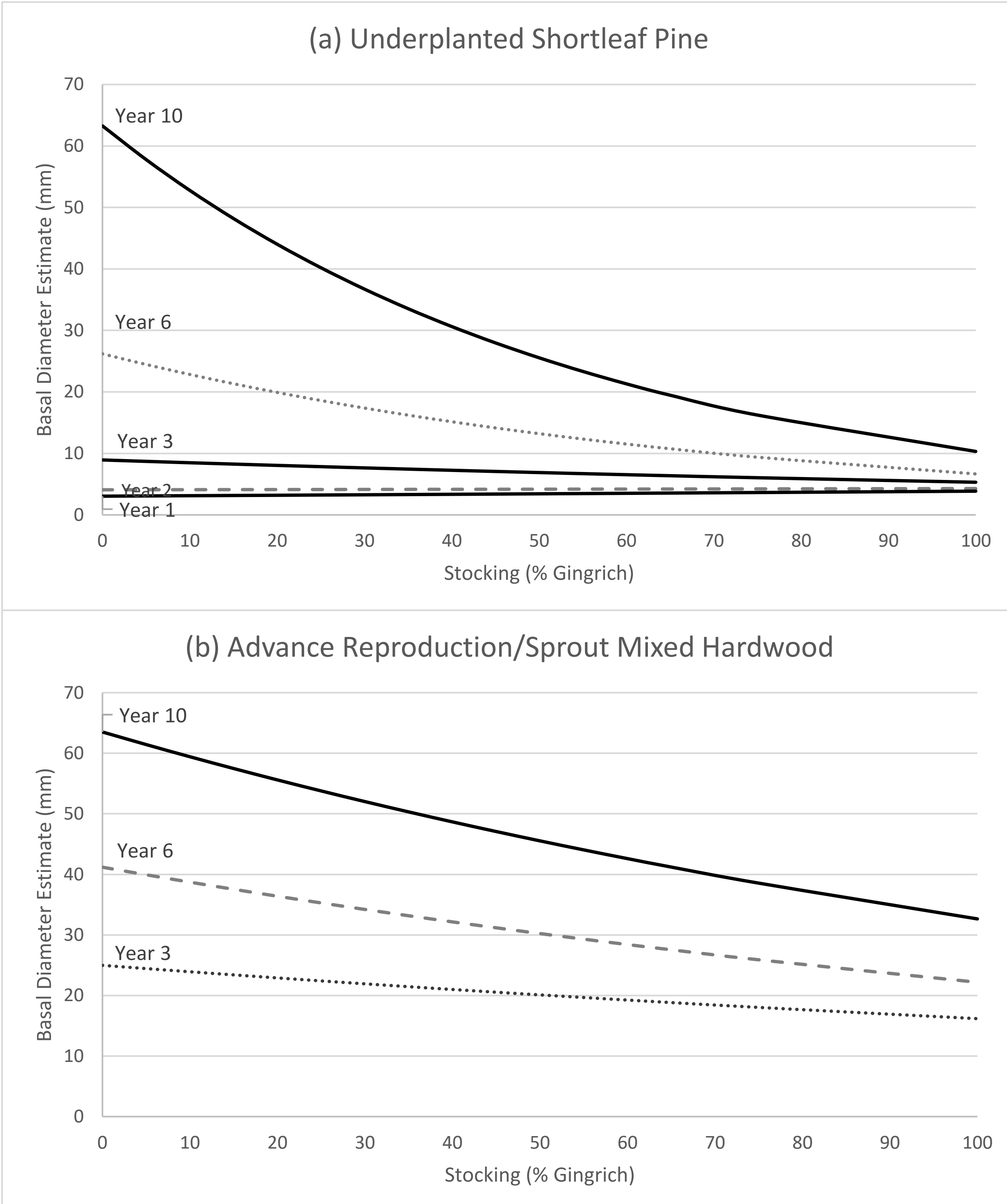

Figure 18. Diameter growth (basal) through time for (a)underplanted shortleaf pine and (b) advance reproduction/stump sprout mixed hardwood trees. Increasing stocking level significantly reduced diameter growth after year 3 in shortleaf pine, and significantly reduced diameter growth in all measurement years for the mixed hardwoods ($p<0.001$). Shortleaf pine was more sensitive to stocking level, as diameter declined more severely than hardwoods as stocking level increased. However, after 10 years, shortleaf pine and hardwoods in 0% stocking (clearcuts) had the same mean diameter at 63mm.

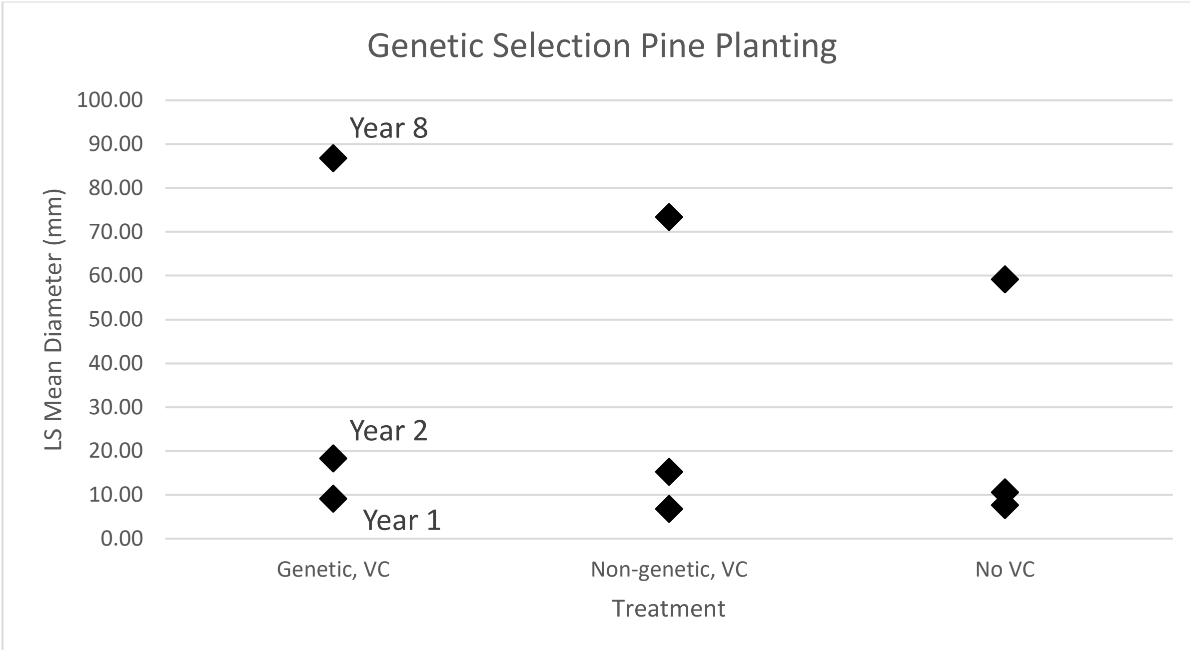

Figure 19. Least-square mean diameter for a genetic selection planting. Years 1 and 2 reflect basal diameter, while year 8 is diameter at breast height (DBH). Vegetation control (VC) significantly increased diameter in each measurement year, while genetic selection with VC provided an additional, significant diameter increase. Values for each year are connected with dashed lines for ease of identification, not to infer any type of relationship between the treatments.

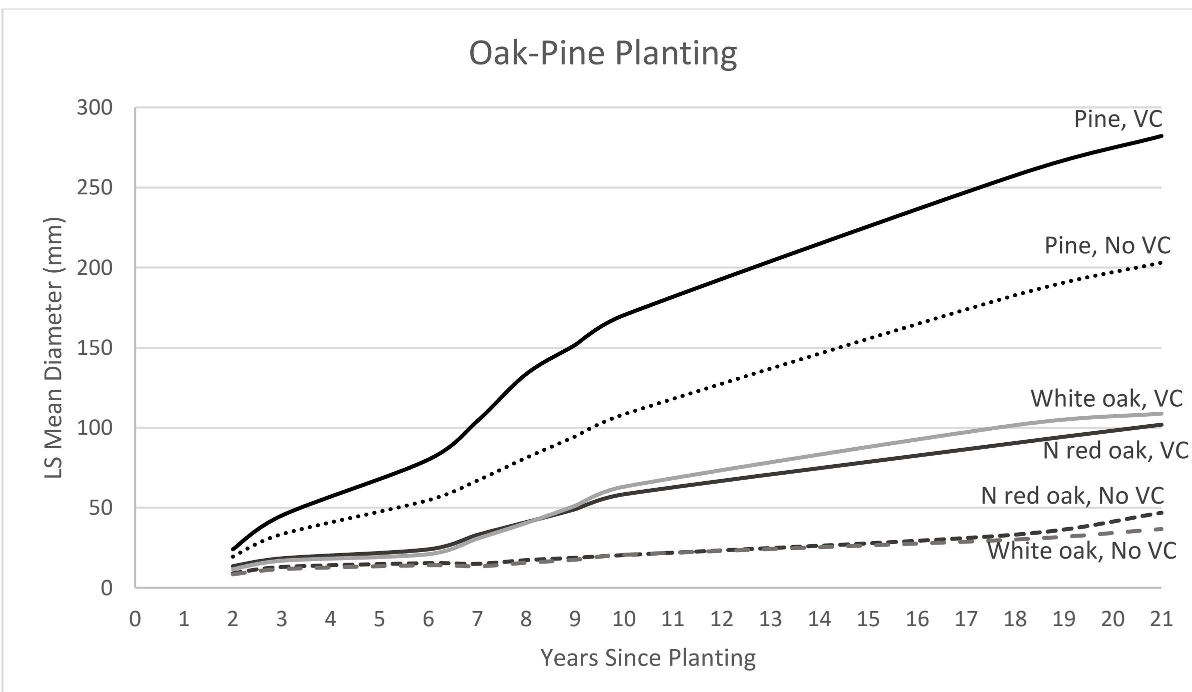

Figure 20. Least-square mean diameter growth, by species and VC treatment in an oak-pine planting. Solid lines indicate VC treatment; dashed lines are no VC. Diameter data were not collected until 2 years into the study. Diameter at breast height (DBH) was collected once trees were >1.5m. Shortleaf pine DBH after 21 years was nearly 2.5 times greater than both white and northern red oaks, even in the no VC treatment. Oaks with no VC were ½ the diameter of oaks with VC.

Discussion

The initial, short-term, and long-term survival of shortleaf pine seedlings was highly variable by site, while less affected by treatment. Increasing overstory stocking did not reduce shortleaf pine survival probabilities in underplanted stands at Sinkin after 10 years, which is consistent with studies performed on the same treatment plots which analyzed early seedling survival (Kabrick et al. 2011, Kabrick et al. 2015). Instead, we see a steady decrease in survival probabilities through time, dropping to just 26%, regardless of overstory stocking level, after the tenth year (Figure 1a). In contrast, genetic selection at the Wurdack pine planting had the most significant impact on survival probability, with 8-year survival over 90%, while non-improved trees in the same site preparation treatments had almost 10% lower survival. Employing genetic selection with other treatments such as ripping, burning, or herbicide has returned similarly high (>80%) survival numbers in previous studies across Missouri and Arkansas (Cain and Shelton 2000, Brissette and Barnett 2003, Gwaze et al. 2006), while genetic selection without the use of VC resulted in a 20% drop in survival probability at Wurdack (Figure 1b). Shortleaf pine survival probability at the oak-pine planting was initially much lower, at 60%, but has remained at 50% through 22 years. It is possible that animal damage and drought around the time of study inception could have disproportionately contributed to the low initial survival numbers of shortleaf pine (Ponder 1997). Though vegetation control (VC) had no significant effect on shortleaf pine survival at the LTSP site, it was a significant effect for both northern red and white oaks, especially after year nine, when understory competition began to reduce survival (Figure 1c). The otherwise high survival of oaks (>80%) is contrary to findings in the literature that conclude planted oak seedlings do not perform adequately in temperate deciduous forests (Dey at al. 2012).

Tree height and diameter growth were more directly affected by treatments than survival. Height and diameter growth of underplanted shortleaf pine was significantly reduced by increasing overstory density after year 3 (Figures 2 and 6). Shortleaf pine can be very sensitive to the presence of an overstory. Both artificial and naturally regenerated seedlings have better height and diameter growth when the overstory density is below approximately 20% (Liming 1946, Guldin and Heath 2001, Blizzard et al. 2007a, Kabrick et al. 2011). We found a 0.5-m increase in height for each 20% decrease in overstory stocking from 100% to 40%, and a 1-m increase for each 20% decrease below a 40% stocking level at year 10; while growth reductions in earlier years were less pronounced (year 6) or even absent (years 1-3). Hardwood height and diameter growth were also reduced by increasing overstory density, albeit to a lesser extent than the planted shortleaf pines. It is notable, however, that the hardwoods originating from advanced reproduction or stump sprouts had the same growth rate as the planted shortleaf pines, although the hardwoods were taller overall through this most recent analysis period (Figure 3).

Similar reductions in height and diameter growth were noted at both the genetic selection pine planting (Figures 4 and 7), and the oak-pine planting (Figures 5 and 8) with respect to vegetation control. The presence of an understory significantly reduced height and diameter growth for northern red oak, white oak, and shortleaf pine through 22 years at the oak-pine plantation, and through 8 years at the pine plantation. The correlation of growth and VC, especially with the two oak species, were identified early on in the LTSP study, while the pine species had a more subtle, though still significant response to the VC treatment (Ponder et al. 1999, Powers et al. 2005, Ponder et al. 2007, Ponder et al. 2012). While competition can drastically reduce the height growth of shortleaf pine, Lyczak (2019b) found no significant difference in height between trees underplanted in clearcuts and those planted with vegetation control. This suggests individual tree characteristics and microsite variations have a more direct impact on growth dynamics than some treatment effects.

While we observed the best survival and growth in the genetic selection pine planting using vegetation control and improved seedlings, monocultures are not representative of Missouri forests. Mixed hardwood-shortleaf pine forests were once abundant in Missouri, support a diverse array of plant and animal species, and could provide much needed resilience and resistance to the effects of climate change (Eddleman et al. 2007, Kabrick et al. 2017). Shortleaf pine can be successfully established through underplanting in an existing stand, but pine reproduction requires release from competition at some point before year ten. Seedlings planted in conjunction with vegetation control for at least two growing seasons do not appear to require intermediate release and have greater overall height and diameter growth. The oak-pine plantation at LTSP demonstrates how a mixed-wood system can be created to favor rapid initial growth of shortleaf pine, while retaining the presence of ecologically and commercially important oak species. Individual restoration goals, desired end condition, and budget should ultimately determine the prescription implemented.

Conclusion

Survival does not appear to be related to the overstory or understory density, though survival was significantly lower without vegetation control in the genetic selection pine planting. Survival results from the underplanting study at Sinkin suggest shortleaf pine should be released sometime between the 3rd and 6th years after planting. Surprisingly, planted shortleaf pine outgrew planted northern red and white oaks in oak-pine plantings. Underplanted shortleaf pine grew at a similar rate to advance reproduction and sprouted hardwoods, though they were shorter overall with smaller diameters than the hardwood cohort. The most favorable combination of survival and growth was obtained with understory vegetation control, but acceptable growth was noted in clearcut plantings. Restoration efforts should focus on initial seedling establishment, with a release sometime before the sixth year of growth.

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Chapter 7:
Summary and Conclusion

The objectives of this study were to 1) determine the survival and growth capabilities of artificial regeneration shortleaf pine seedlings when i) planted as a minor component with northern red oak and white oak, ii) underplanted in existing mixed-hardwood stands, and iii) planted alone in a genetic selection planting, 2) identify barriers to shortleaf pine establishment in the Missouri Ozarks, and 3) create height-growth percentiles that can be used to predict future survival and growth. Several analysis techniques were employed to accomplish those objectives, including: analysis of individual sites and their corresponding treatment effects, comprehensive analysis across all three study sites using treatments or variables common across each site.

Analyses of treatment effects including soil compaction, biomass removal, vegetation control, and genetic selection show that shortleaf pine survival probability is highly variable and not consistent by treatment. At LTSP, survival probability increased when the soil was compacted to moderate and severe levels-but was unaffected by VC understory treatments. Similarly, the survival study of underplanted seedlings at Sinkin showed no relationship between survival probability and overstory stocking levels, even when seedlings were planted in fully stocked plots. The LTSP VC results contrast with those from the Wurdack analyses, where understory VC treatments increased survival probabilities by over 30% after 8 years. Overall, the best survival occurred when seedlings were either taller than their nearest competitor or were both genetically selected and planted in a VC treatment.

Height growth analyses were more consistent across treatments and sites, with trends reflecting the expected outcomes. At LTSP, biomass removal, compaction, and VC all increased tree heights throughout the study period. Genetic selection and VC both significantly increased tree heights at Wurdack. On the Sinkin, tree heights significantly increased as the overstory stocking level decreased, while trees in stands with stocking of 15% or less were statistically similar in height to trees at both LTSP and Wurdack. Thus, while genetic selection and VC provided statistically significant gains in mean height, orchard run seedlings underplanted in lower density stands had practically the same average height. It is worth noting that the height growth analysis of planted and advance reproduction/ sprouted hardwoods revealed two surprising trends: planted shortleaf pine drastically outgrows both planted northern red and white oaks and grows at the same rate as advance reproduction/ sprouted hardwoods (after year 3) when competing directly for resources.

Diameter growth was most significantly reduced by the presence of both overstory and understory competitors. At LTSP, the effect of VC on diameter was far greater than on either survival or height for all three species. Increasing overstory stocking levels had a detrimental effect on diameter growth at Sinkin for both planted shortleaf pine, and the advance reproduction/ sprouted hardwoods, though surprisingly the diameters of both the pines and the hardwoods in the low stocking level treatments were statistically the same. At Wurdack, even genetically selected trees had reduced diameters in the no VC treatment, suggesting limits to the ability of genetics to compensate for competition from the understory.

When considering the importance of seedling establishment and early growth to shortleaf pine regeneration, competition can be identified as the most significant barrier to restoration success. While competition does not directly reduce survival in these studies, it does significantly reduce both height and diameter growth, which are essential to the long-term ability of shortleaf pine to recruit into a dominant or co-dominant position prior to canopy closure in the stand development process.

Given these conclusions, the height-growth percentile charts developed become an invaluable tool to quickly and easily assess individual seedling growth, without the need of complicated calculations. Height-growth percentiles can accurately assign seedlings to a growth category, and accurately predict future developmental potential. This knowledge would allow land managers to identify potential reforestation failures much earlier than other tools allow and provide an opportunity to apply intervening treatments to improve the health and vigor of targeted trees. Though these curves were derived from an extensive dataset of over 5,500 individuals, there is a need to increase the diversity of the data used to include shortleaf pines from additional provenances, physiogeographic regions, and planting schemes. As the source information grows, so will the accuracy of the percentiles, the predictive power associated with them, and the applicability across the range of shortleaf pine.