

**Controlling Woody Vegetation for the Underplanting and
Reintegration of Shortleaf Pine into Upland Hardwood Forests of
the Southeast**

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Max Street
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Abstract

Shortleaf pine (*Pinus echinata* Mill.) has the widest distribution of any pine species in the southeastern United States. Shortleaf pine is an important softwood commercial timber species, second only to loblolly pine (*Pinus taeda*). The amount of shortleaf pine has diminished dramatically beginning in the early 19th century.

The decline of shortleaf pine has been attributed to several, primarily societal factors. Old field abandonment has declined which provided optimum seed bed conditions for the establishment of shortleaf pine. The timber industry began to favor the faster-growing loblolly pine with shorter stand rotations at the expense of shortleaf pine (Bragg, 2016). The Smokey Bear campaign also played a role in the reduction of natural and anthropogenic-related wildfires that created the early successional habitat conditions necessary for the growth and natural regeneration of shortleaf pine (Smith, 2017). Along with southern pine beetle (SPB) infestations (Oswalt et al., 2016), these events led to the eventual decline of shortleaf pine.

Historically, shortleaf pine forest types were a common occurrence in the southeastern US uplands. After a wildfire occurrence in November 2016 on the University of Tennessee Cumberland Forest, within a subregion of the Cumberland Plateau, a research project was initiated in order to reintegrate shortleaf pine into the hardwood upland forests where shortleaf pine was once a dominant species. In February 2018, an herbicidal application of imazapyr was

administered on an unburned adjacent stand to a burned section of the forest, followed by an underplanting of shortleaf pine seedlings on both treatment sites. The objective was to compare the amount of available light with the use of a ceptometer, measuring photosynthetic active radiation, provided by the treatments and how available light affected seedling survival, height growth, and root collar diameter growth.

Results from this study suggest that the establishment of underplanted shortleaf pine would benefit more from the use of herbicides rather than fire in mature upland stands. Root collar diameters were not statistically different, though the fire plots had numerically greater growth in diameter. Furthermore, PAR values had no significant effect on seedling height and seedling root collar diameter during the experiment.

Table of Contents

CHAPTER 1: INTRODUCTION.....	1
CHAPTER 2: LITERATURE REVIEW	2
Shortleaf Pine as a Resource	2
Shortleaf Pine Silviculture.....	2
Land Use Changes and the Decline of Shortleaf Pine	5
CHAPTER 3: HYPOTHESIS & OBJECTIVES.....	8
Hypothesis	8
Objectives	8
CHAPTER 4: METHODS	9
STUDY SITE & HISTORY	9
Wildfire.....	12
Herbicide	13
Shortleaf Pine Underplanting	14
Community Descriptions.....	14
Plot Design.....	17
Data Collection & Measurements	17
Data Analysis.....	19
CHAPTER 5: RESULTS	23
Seedling Survival	23
Seedling Height.....	23
Seedling Height.....	23
Root Collar Diameter.....	25
Photosynthetic Active Radiation (PAR).....	25
CHAPTER 6: DISCUSSION.....	29

Survival Rate	29
Seedling Height.....	29
Seedling Diameter	31
Stand Predictions	31
Management Implications	34
CHAPTER 7: CONCLUSIONS	37
REFERENCES	38
APPENDICES	44
VITA	46

List of Tables

Table 1. Dates of events for shortleaf pine study in east Tennessee.....	22
Table 2. Shapiro-wilks test for normality for shortleaf pine seedling root collar diameter and height	22
Table 3. Levene test for equal variance for shortleaf pine seedling root collar diameter and height	22
Table 4. Year, treatment, number of seedlings, mean height, error rate, and letter group for shortleaf pine seedlings.....	24
Table 5. Year, treatment, number of seedlings, root collar diameter, error rate, and letter group for shortleaf pine seedlings	24
Table 6. Year, treatment, number of seedlings, mean survival rate, error rate, and letter grouping for shortleaf pine seedlings	27
Table 7. Survival rate of shortleaf pine seedlings per plot and control from 2019 to 2020.....	27

List of Figures

Figure 1. Natural Range of Shortleaf Pine by E.L. Little 1971, USDA Forest Service.....	3
Figure 2. Historical image of the University owned property showing shortleaf pine as the dominant tree species.	11
Figure 3. Plot 3 at the herbicide study site.	16
Figure 4. Plot 6 at the wildfire study site	16
Figure 5. Chestnut oak reproduction in the herbicide study area.....	18
Figure 6. Google Earth image of shortleaf pine research study area.....	18
Figure 7. Plot outline with light measurement reference points.....	20
Figure 8. Average PAR measurements at plot locations for 2019 and 2020.....	28

Chapter 1: Introduction

Shortleaf pine has the widest distribution of any pine species in the southeastern United States. Historically, shortleaf pine was an important softwood commercial timber species, second only to loblolly pine. The amount of shortleaf pine has diminished dramatically beginning in the early 19th century. The decline of shortleaf pine has been attributed to several, primarily societal factors. Old field abandonment has declined which provided optimum seed bed conditions for the natural establishment of shortleaf pine. The timber industry began to favor the faster-growing loblolly pine with shorter stand rotations at the expense of shortleaf pine (Bragg, 2016). The Smokey Bear campaign also played a role in the reduction of natural and anthropogenic related wildfires that created the early successional habitat conditions necessary for the growth and natural regeneration of shortleaf pine (Smith 2017, Lawson 1990). Along with southern pine beetle (SPB) infestations (Oswalt et al., 2009), these events led to the eventual decline of shortleaf pine. Few natural remnants remain; consisting mostly of solitary trees or groups of a few mature trees with little likelihood of natural regeneration without a disturbance event to create exposed soil and sunlight for seed germination (Clabo, 2014).

Chapter 2: Literature Review

Shortleaf Pine as a Resource

Shortleaf pine is the most wide spread of the southern pine species in the eastern United States, encompassing 241 million acres in 22 states ranging from north Florida to as far west as east Texas and as far north as southern New York (Figure 1). Shortleaf pine can be found in various forest types as the dominant species, primarily the shortleaf pine type at 3.3 million acres and the shortleaf pine-oak type at 2.9 million acres for a total of 6.2 million acres (Oswalt, 2012). Of the estimated 1.9 billion trees of shortleaf pine growing stock, 53 percent are found in just three states; Mississippi at 195.4 million trees, Oklahoma at 313.4 million trees, and Arkansas at 509.8 million trees. Comparatively, Tennessee contains 32.2 million trees of the total growing stock (Moser et al., 2007). As of 2017 the most planted forest type group in the Southeast is loblolly-shortleaf pine at 34 thousand acres per year, making up 71 percent of all planted forests in the southern United States (Oswalt et al., 2019).

Shortleaf Pine Silviculture

Growing conditions for shortleaf pine range from old fields to floodplains, to rocky slopes in upland forests. Shortleaf pine is notorious for its ability to grow on low quality sites though the species grows best in deep, well-drained soils found mostly in the flood plains on the South Atlantic and Gulf Coastal plains. The soils in which shortleaf pine mostly inhabit are from the order Ultisols and suborder Udults. This freely draining soil order contains a humus deficient topsoil with a

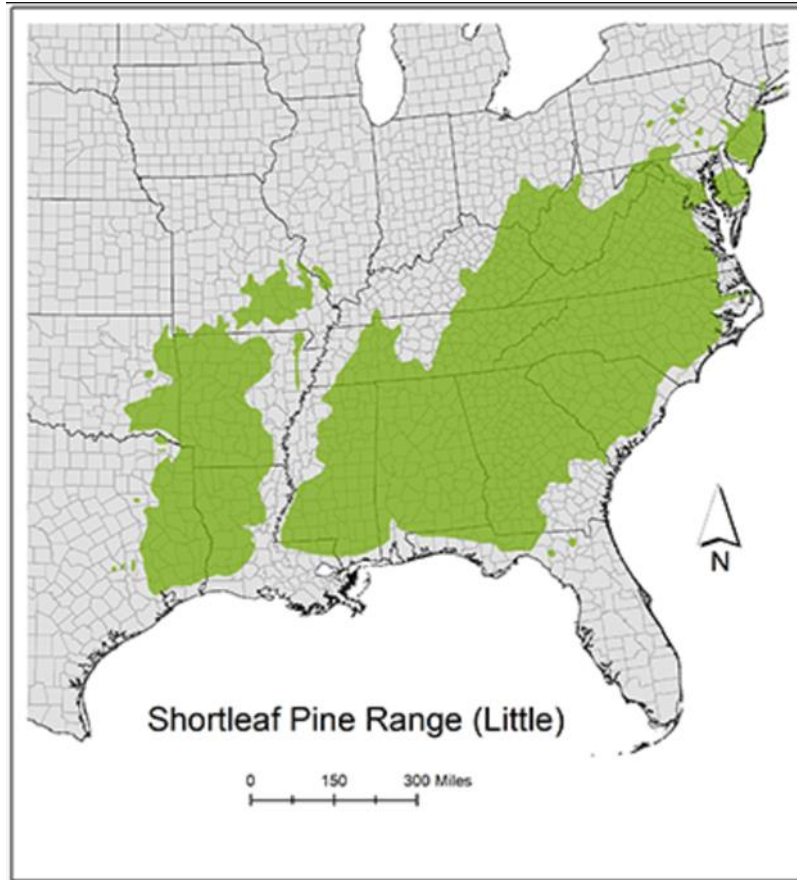


Figure 1. Natural Range of Shortleaf Pine by E.L. Little 1971, USDA Forest Service

udic moisture regime i.e., the soil moisture level seldom falls below the rate of evapotranspiration (Lawson, 1990). Seed production and dissemination occur in late fall after maturity but can continue falling into mid-spring. Shortleaf pine cones generate 2 to 3 dozen seeds a piece with trees producing up to 500 cones. In the southern US, heavy cone crops occur every 3 to 6 years. After winter stratification, epigeous germination ensues in early spring. Soil scarification, whether natural or anthropogenic, increases initial seedling establishment (Lawson 1990).

Shortleaf pine fares well both in pure and mixed stands and is a key element of three forest cover types; shortleaf pine (type 75), loblolly pine-shortleaf pine (type 80), and shortleaf pine-oak (type 76) (Lawson, 1990). In mixed stands, it occurs naturally with other southern yellow pines such as loblolly pine, longleaf pine (*Pinus palustris*), and slash pine (*Pinus elliottii*). Primarily, it will be found in association with loblolly pine in planted stands where this forest type accounts for 71 percent of all planted forests in the Southeast (Oswalt et al., 2019).

In a mixed pine-hardwood forest, shortleaf pine can be found with a vast array of hardwood tree species such as sweet gum (*Liquidambar styraciflua*), white oak (*Quercus alba*), red maple (*Acer rubrum*), scarlet oak (*Quercus coccinea*), southern red oak (*Quercus falcata*), tulip poplar (*Liriodendron tulipifera*), and chestnut oak (*Quercus montana*), amongst others. Shortleaf pine-oak forest types are commonly temporary, especially on high quality sites where shortleaf pine gives way to hardwoods without any disturbance events to set the

hardwood forest component back in succession and create favorable seedbed conditions for the establishment of shortleaf pine, thus this forest type can be thought of as a provisional forest type that will eventually give way to mature hardwoods (Lawson 1990).

If a shortleaf pine component was to be established within an existing hardwood stand, competition control of hardwood regeneration was typically advocated, especially if shortleaf pine development was for timber production rather than ecological function. Also, the lag time in growth while developing its extensive root system made it difficult to compete against hardwood regeneration on highly productive sites (Kabrick et al., 2015). In recent years, the advocacy for the retention of a hardwood overstory has been suggested for shortleaf pine establishment in a hardwood dominated forest. This is more visually appealing for landowners and managers than a complete overstory removal or clear cut. Furthermore, the retention of an overstory can help partially control surrounding woody competition (Jensen et al., 2007).

Land Use Changes and the Decline of Shortleaf Pine

The amount of shortleaf pine in the eastern United States has diminished dramatically. The decline of which has been attributed to several, primarily societal factors. Forest inventory and analysis (FIA) data from 1980 attributes 12.6 million acres of shortleaf pine-dominated forests occurred on timberland, which is defined as forest land that has not been administratively removed from timber production through statute or law; comparatively, in 2010 there was an

estimated 6.1 million acres of shortleaf pine-dominated forests in the eastern United States. This equates to a 52% loss of shortleaf pine-dominated forests over a 30-year period (Oswalt 2012).

Shortleaf pine was historically a favored timber species amongst other pine tree species found in the eastern US. By the middle of the 20th century, the timber industry began to favor the faster-growing loblolly pine with shorter stand rotations at the expense of shortleaf pine (Bragg, 2016). From 1960 to 1989, loblolly pine commercial forestlands increased from 28.6 million acres to 33.8 million acres in the South (Shultz 1997). By the late 1990's, that number climbed to 39.3 million acres (South and Buckner, 2004). Loblolly pine is now the second most abundant tree species, replacing many areas formerly composed of shortleaf pine, in the contiguous United States at 22 billion trees, behind red maple at 25 billion trees (Oswalt et al., 2019).

During the same time period in 1944, the Smokey Bear Campaign was implemented by the United States Forest Service (USFS) in order to promote forest fire prevention. Though well meaning, the Smokey Bear Campaign prevented anthropogenic fires along with natural wildfires that had historically occurred across the US. These fires created optimal seedbed conditions by scarification or burning. Abandoned agricultural fields and cutover timberlands that once favored shortleaf pine, now favored loblolly pine with the more numerous seed production. Loblolly pine took advantage of shortleaf pine with its

faster growth rate and regeneration, and swiftly expanded its distribution (Clabo and Clatterbuck 2015).

Introgression, or hybridization, of shortleaf with loblolly pine is another factor in shortleaf pine decline. Since the middle of the 20th century, introgression between shortleaf pine and loblolly pine has increased from 3 percent to roughly 45 percent (Stewart et al., 2012). This phenomenon has been exacerbated primarily by the reduction in wildfire which favored shortleaf pine over other southern yellow pine species. Shortleaf pine seedlings contain a unique adaptation, a basal crook, which lowers dormant buds to the soil surface where they are sheltered from fire to enable resprouting after topkill (Bradley et al., 2016).

Few natural shortleaf pine remnants remain, consisting mostly of solitary trees or groups of a few mature trees. Without a disturbance event to create exposed soil and infiltration of sunlight for seed germination, natural regeneration of shortleaf pine is not likely (South and Buckner, 2014).

Chapter 3: Hypothesis & Objectives

Hypothesis

Shortleaf pine seedlings planted in the treatment area where herbicide application was used to suppress competing vegetation will have greater survival and increased height and diameter growth than those planted in the wildfire area.

Objectives

- 1.) To compare the survival rate of underplanted shortleaf pine seedlings after fire and herbicide application of woody vegetation after three growing seasons.
- 2.) To compare the height of underplanted shortleaf pine seedlings after fire and herbicide application of woody vegetation after three growing seasons.
- 3.) To compare the root collar diameter growth of underplanted shortleaf pine seedlings after fire and herbicide application of woody vegetation after three growing seasons.
- 4.) To compare the amount of photosynthetically active radiation created by wildfire and herbicide application of competing vegetation on the height and root collar diameter growth of underplanted shortleaf pine seedlings after three growing seasons.

Chapter 4: Methods

Study Site & History

The study site is located in south Morgan County, Tennessee, in the Little Brushy Mountain Unit of the Cumberland Forest, part of the level III ecoregion (Griffith et al., 1998). The property was purchased in 1936 by the University of Tennessee and is part of the Institute of Agriculture Forest Resources Research and Education Center (FRREC).

The study area is in the southern foothills of the Cumberland Mountains and is characterized with a weakly dissected surface with a primarily shale bedrock, but also sandstone. Silt loams are the major soils and are classified as acidic with low fertility (Smalley 1984). Slopes range from 35 to 80 percent with a depth to the water table of more than 80 inches. The drainage class is classified as well to excessively drained (USDA 2012). Site indices at base age 50 are 55 feet for shortleaf pine and chestnut oak, and 60 feet for black oak (*Quercus velutina*), southern red oak, and Virginia pine (*Pinus virginiana*) (USDA 2012, Smalley 1984).

The climate in Morgan County is characterized as long, moderately hot summers with short, mild winters (Thorntwaite, 1948). The mean temperature for the region is 56 degrees Fahrenheit with local temperatures varying greatly due to differences in elevation, cloud cover, and aspect. Mean annual temperature is about 59 inches, though brief intervals of very dry or very wet weather are common throughout the year (Smalley 1984).

The research site vegetation is characterized as a mixed mesophytic though varies considerably due to shading of adjacent land masses and aspect (Griffith et al., 1998). Historically, this was a pine-oak dominated forest where the vast majority of dominant tree species were shortleaf pine (Figure 2). Reasons for the dominance of shortleaf pine on the property are of both natural and anthropogenic causes that can be traced back to the late 19th and early 20th centuries.

A report from an initial timber sale on the University-owned property in June of 1950 stated that between 1915 and 1920 most of the tulip poplar, chestnut oak, red oak (*Quercus spp.*), and white oak had been cut, leaving less desirable species to reseed the area. Mining had been widespread throughout the area for decades and the report stated that extensive areas around many of the old mine openings had also been stripped bare of vegetation. Also, fire protection in Morgan and Scott Counties was virtually nonexistent until the middle of the 20th century.

In short, natural wildfires had historically created the ideal initial seedbed conditions for shortleaf pine establishment and regeneration. Furthermore, timber harvesting of hardwoods and land clearing for mining operations had created a model environment for shortleaf pine growth and dominance for the future of the forest. Once the University of Tennessee had purchased the property in 1936, timber harvesting had abruptly stopped, and fire suppression had now taken hold. A study in 1966 found that, at the time, one-quarter of the forest's density



Figure 2. Historical image of the University owned property showing shortleaf pine as the dominant tree species (Image courtesy of Martin Schubert).

and one-fifth of the basal area were shortleaf pine on southern slopes but that the shortleaf pine-oak forest type should be considered a temporary forest type here due to the understory being occupied by hardwoods (Martin III, 1966).

In 1999, the southern pine beetle (SPB) outbreak occurred across Tennessee and lasted until 2002. This was a significant disturbance event and was the worst outbreak in Tennessee since the 1970s. The greatest impact from the outbreak occurred east of the Tennessee River where an average of 8.5 million trees per year were lost followed by the Plateau with 6.3 million trees per year (Oswalt et al., 2009). This insect outbreak had a significant impact on Cumberland Forest. Shortleaf pine was already being replaced by hardwoods and the SPB outbreak decimated the shortleaf pine component that remained, leaving sparsely-scattered, mature, individual stems only.

Wildfire

During 2016, an extended period of drought occurred in Tennessee which led to numerous fires for the fall fire season. These fires were atypical in their intensity in which they burned and their severity on the natural vegetation (Schubert et al., 2020). Though not exceptional, during the time period from December 2015 to November 2016, there was a record of maximum air temperatures across east Tennessee for a few days in late October and early November. A noteworthy incident during this time period occurred in late November in Gatlinburg, Tennessee in the Great Smoky Mountains National Park dubbed the Chimney Tops 2 (CT2) fire. Record air temperatures coupled

with strong wind gusts made this human-induced fire burn approximately 17,000 acres, making it the largest fire in the history of the Great Smoky Mountains National Park (USDI 2017, Schubert et al., 2020).

During the same time period as the Chimney Tops 2 fire, a human caused fire named the Little Brushy Wildfire occurred in Morgan County in November 2016 burning approximately 2,200 acres, 500 acres of which were on the University of Tennessee's Cumberland Forest near Coalfield, Tennessee (Schubert et al., 2020). This was a mixed-severity fire with some high-severity impacts. Sharp ridges and deep coves in the terrain helped funnel the fire upwards, acting as a furnace on the surrounding vegetation. At the same time, the fire slowly rolled down slope, not affecting the surrounding vegetation as harshly as when moving up slope.

Herbicide

In February 2018, an herbicidal application of imazapyr ready to use (RTU) was administered via the hack and squirt method on the hardwood overstory of an adjacent stand to a burned area of the forest by the forest management crew with the help of wildlife and forestry students at the University of Tennessee. Imazapyr is categorized as an amino acid synthesis inhibitor, which prevents the manufacture of individual amino acids that disrupt normal plant growth leading to eventual mortality. The application of imazapyr was not diluted and used as is.

The objective of this herbicidal application was to eliminate the hardwood overstory so as to allow light down to the forest floor for the ensuing shortleaf

pine seedling planting. The hardwood overstory at this site primarily consisted of red maple and chestnut oak, with fewer stems of northern red oak and scarlet oak also being present.

Shortleaf Pine Underplanting

In April 2018, a planting crew performed an underplanting of bare root shortleaf pine seedlings from the Tennessee State Nursery beneath the decaying hardwood overstory. Underplanting can be defined as the deliberate underplanting of understories of shade-tolerant species beneath taller trees (Smith et al., 1996). Yet, evidence has been shown that even though shortleaf pine is a shade-intolerant species, it can grow, albeit more slowly, and survive beneath a partially removed understory (Guldin and Heath 2001) along with enduring competition from other tree species (Lawson 1990). Shortleaf pine seedling planting is not recommended after May due to potential loss from drought and competition from established flora (Lawson, 1990), though in this instance, competition in the understory was limiting and the hardwood overstory has been largely removed. Seedlings were planted in a randomized fashion across both treatment sites, occupying an average area of 144 square feet (12 ft x 12 ft) per seedling or approximately 300 seedlings per acre.

Community Descriptions

At the time of planting, both treatment sites were classified as a mixed hardwood stand with chestnut oak, and sparsely scattered northern red oak, as the dominant tree species in the stands. Red maple made up the codominant

and intermediate crown classes (Figure 3 and Figure 4). An average of 45 stems per acre were recorded for chestnut oak and twenty stems per acre for red maple. Diameter at breast height (DBH) measurements taken within plots indicate chestnut oak had the overall larger diameters at both treatment sites with most diameters being in the standard size class (12 to 24-inches) with two stems at each treatment site reaching into the veteran size class (greater than 24-inches). Red maple at both sites were in the standard size class with diameters not reaching over 15-inches. Northern red oaks were all in the standard size class, leaning towards the larger diameter range.

The midstory of the herbicide treatment plots were comprised of black gum (*Nyssa sylvatica*), sourwood (*Oxydendrum arboretum*), flowering dogwood (*Cornus florida*), and white pine (*Pinus strobus*). At the wildfire plots, the midstory consisted of sourwood, red maple, and chestnut oak.

Regarding regeneration within the plots, it should be noted that regeneration was sparse across all noted species with the exception of the aforementioned plethora of chestnut oak in the herbicide plots and the increased density of hickory and sassafras (*Sassafras albidum*) regeneration in the wildfire plots (Figure 6). Concerning red maple in the codominant and intermediate crown classes at both treatment sites, most all stems of *Acer rubrum* succumbed to mortality from the herbicide and at the same time, vigorous growth from root sprouting occurred. Only in the wildfire plots where the fires intensity and severity were most grievous were red maple killed from the canopy to the root system.



Figure 3. Plot 3 at the herbicide study site.

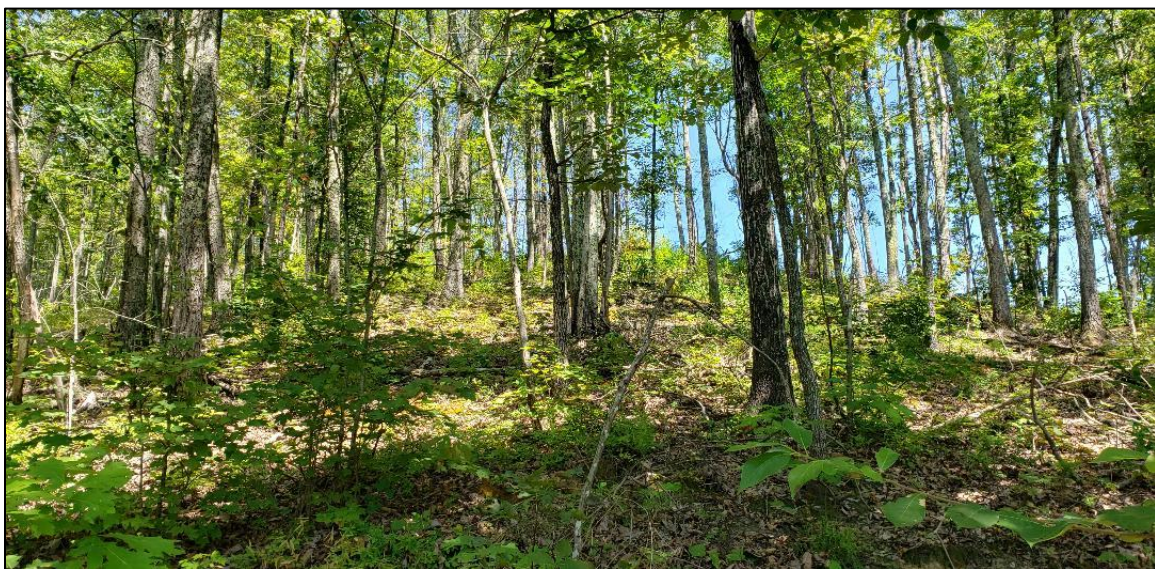


Figure 4. Plot 6 at the wildfire study site

Plot Design

Both the burned and herbicide application area encompass 10-acres total. Six strip plots measuring 23 x 200 feet were assigned to each treatment area for a total of 12 plots, giving an 11 percent sample size of the total area (Figure 7). Plots were oriented in well-defined North and South aspects. All seedlings located within the plots were sampled. The control is located on an unimproved road along the ridge top with no competing vegetation in full sunlight. The control is approximately one acre and all planted shortleaf pine seedlings were sampled. A reel tape was used in conjunction with a compass to establish hardline boundaries for each plot.

Data Collection & Measurements

To measure and interpret available light to the planted seedlings, a ceptometer was used to measure photosynthetically active radiation (PAR) in the 400 to 700 nanometer wavebands. This waveband represents the solar spectrum which plants use for photosynthesis. PAR measurements are used as a way to measure light interception in plant canopies. For this study, PAR measurements were recorded to coincide with the planted seedlings growth in height and diameter.

Light readings were taken near the end of the growing season in late August of 2019 and 2020 on cloudless days between 10 AM and 2 PM, in order to take advantage of solar noon i.e., when the sun is at its highest point in the sky based on time of year and physical location.



Figure 5. Chestnut oak reproduction in the herbicide study area.



Figure 6. Google Earth image of shortleaf pine research study area.

Each light measurement was taken on a South facing aspect at approximately three feet from the forest floor for below canopy measurements. Above canopy measurements were taken in a completely open setting on a ridge top absent of any plant foliage impeding PAR readings. Each strip plot received a total of 15 measurements for available light at 0', 10', and 20' horizontally and 0', 50', 100', 150', and 200' vertically, respectively (Figure 8).

A digital caliper was used to measure the root collar diameter of each surviving seedling to 1/10 of an inch in all plots. The total height of each seedling was measured with a ruler to the nearest half inch. Along with the aforementioned measurements, planted seedling mortality within each plot was also recorded. The diameter tape was used to measure the diameter at breast height (DBH) of all trees located in the overstory and midstory within each plot.

The GPS location of the four corners of each plot was recorded and marked with flagging. Repeat measurements were taken at the end of the third growing season in 2020. A timeline of the wildfire, herbicide application, shortleaf pine underplanting, and field data collection are presented in Table 1.

Data Analysis

Analysis of variance (ANOVA) was used to test for statistical differences between treatments for growth in height and diameter amongst the underplanted shortleaf pine seedlings.

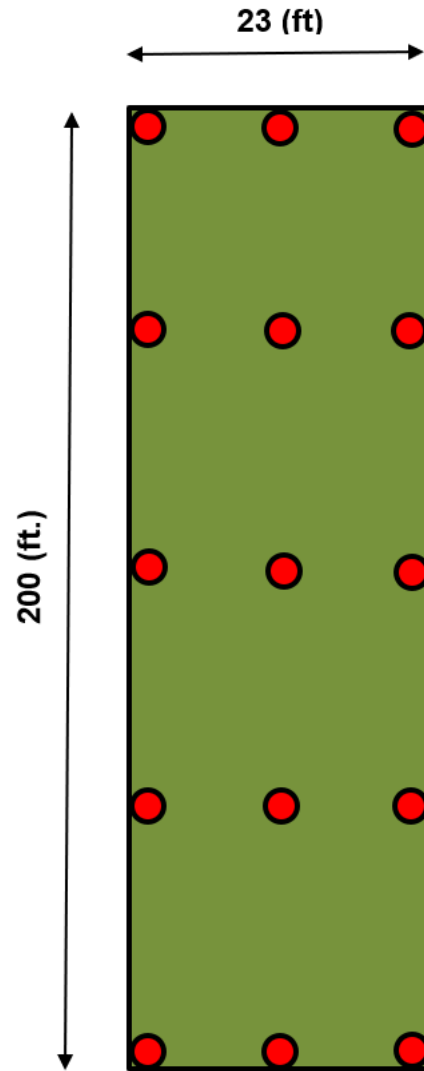


Figure 7. Plot outline with light measurement reference points

Data were analyzed as a complete randomized repeated measures design with sampling using PROC GLIMMIX in SAS 9.4 (SAS Institute 2015). In order to have a balanced design, data from plots were analyzed as least square means; doing so adjusts the model for the covariate and the uneven amount of height and diameter observations between individual plots. Because the plots were measured at years 2019 and 2020, the year was treated as a repeated factor. PAR was used as a covariate in the model to control the effect on seedling height and diameter.

A mixed effect ANOVA was used to analyze the data with year and treatment as fixed factors. Plots within treatments, along with the year and plot nested within treatment were treated as random factors due to the differences in plots. Two-way ANOVA was used to test for statistical differences in survival rates between the year, treatment, and year by treatment interaction. The control was not factored into the two-way ANOVA and simple means are presented.

ANOVA letter groupings were used to indicate significant differences in least square means. Shapiro-Wilk test (Table 2) was used to evaluate normality of ANOVA residuals. A Levene test (Table 3) was used to assess the equality of variances for the residuals. A significance level of $P=0.05$ was used. All statistical assumptions regarding normality were met. Equality differences were significant but standard deviations remained within five-fold, indicating variances are sufficiently equal.

Table 1. Dates of events for shortleaf pine study in east Tennessee

Event	Time
Wildfire at Cumberland Forest	Nov. 2016
Herbicide application	Feb. 2018
Shortleaf pine seedling underplanting	Apr. 2018
Field Measurements	Aug. 2019 ^A
Field Measurements	Aug. 2020 ^B

A. End of second growing season

B. End of third growing season

Table 2. Shapiro-Wilks test for normality for shortleaf pine seedling heights and root collar diameters

	Test	Statistic		p Value	
Height	Shapiro-Wilk	W	0.933	Pr < W	<0.0001
	Test	Statistic		p Value	
Diameter	Shapiro-Wilk	W	0.963	Pr < W	<0.0001

Table 3. Levene Test for equal variance for shortleaf pine seedling heights and root collar diameters

	Obs	year	trt	stddev_y	LeveneP
Height	1	2019	fire	3.450	0
	2	2019	herb	3.723	.
	3	2020	fire	5.762	.
	4	2020	herb	7.050	.
	Obs	year	trt	stddev_y	LeveneP
Diameter	1	2019	fire	0.075	0.048
	2	2019	herb	0.053	.
	3	2020	fire	0.085	.
	4	2020	herb	0.073	.

Chapter 5: Results

Seedling Survival

There were significant statistical differences in survival rates among years ($P=0.0006$) and treatments ($P=0.0048$). Year by treatment interactions had no significant differences ($P=0.7499$). The control and fire plots (Table 4 and Table 5) had the highest survival rates at 73 percent and 71 percent, respectively. The herbicide plots contained the lowest survival rates.

Seedling Height

There were significant statistical differences in seedling heights among treatments and the control ($P<0.0001$). The PAR covariate did not statistically affect seedling heights ($P=0.118$). Statistical differences in seedling heights in the herbicide plots were present from year 2019 to 2020 ($P=0.002$) and also seedlings in the 2019 fire plots to 2020 herbicide plots ($P=0.003$). The most height growth occurred in the control and herbicide plots from (Table 6). No statistical difference existed in the burned plots from 2019 to 2020 when compared to each other. The largest difference in height existed between the burned 2019 plots and the 2020 control.

Seedling Height

There were significant statistical differences in seedling heights among treatments and the control ($P<0.0001$). The PAR covariate did not statistically affect seedling heights ($P=0.118$).

Table 4. Year, treatment, overall number of live seedlings, LS mean number of live seedlings per plot, error rate^A, and letter grouping for shortleaf pine seedlings.

Year	Treatment	Number of seedlings	LS Mean	Standard Error	Letter Group
2019	Fire	130	21.7	1.3	A ^B
2020	Fire	95	16	1.3	A
2019	Herbicide	103	17.2	1.3	B
2020	Herbicide	74	12.3	1.3	B

A. Standard error rates are equivalent due to a balanced design of least square means among years and treatment.

B. Different letters in the same column indicate significant differences (P=0.05).

Table 5. Survival rate (Percentage) of shortleaf pine seedlings per plot (200' x 23') and control (735' x 30') from 2019 to 2020.

Plot	Live Seedlings 2019	Live Seedlings 2020	% Survival
H1	14	8	57%
H2	16	11	69%
H3	20	13	65%
H4	20	15	75%
H5	17	14	82%
H6	16	13	81%
F1	19	18	95%
F2	22	17	77%
F3	23	17	74%
F4	17	10	59%
F5	20	15	75%
F6	29	19	66%
Control	52	38	73%

Statistical differences in seedling heights in the herbicide plots were present from year 2019 to 2020 ($P=0.002$) and also seedlings in the 2019 fire plots to 2020 herbicide plots ($P=0.003$).

The most height growth occurred in the control and herbicide plots from (Table 6). No statistical difference existed in the burned plots from 2019 to 2020 when compared to each other. The largest difference in height existed between the burned 2019 plots and the 2020 control.

Root Collar Diameter

Significant statistical differences were found in seedling root collar diameters between both treatments and the control ($P<0.0001$) (Table 7). Statistical differences existed between 2019 herbicide plots and 2020 wildfire plots ($P=0.037$). The PAR covariate had no significant effect on seedling root collar diameters ($P=0.09$). The fire plots and 2020 herbicide plots shared similarities with each other with the exception of the 2019 herbicide plots. The herbicide plots and 2019 fire plots shared similarities with the exception of the 2020 wildfire plots. The largest root collar diameters, aside from the control (1.22 inches), were found in the 2020 fire plots measuring 0.25 inches (Table 7).

Photosynthetic Active Radiation (PAR)

PAR had no statistical effect on seedling diameter ($P=0.0926$) or seedling height ($P=0.1183$). For 2019, the herbicide plots contained the lowest PAR measurements with a mean of 264 micromoles and the burned plots at 563

micromoles. In 2020, the gap in PAR closed considerably with the herbicide plots containing a mean of 469 micromoles and the fire plots at 470 micromoles (Figure 9). The control had a mean PAR of 1591 micromoles in 2019 and 1566 micromoles in 2020.

Table 6. Year, treatment, number of seedlings, LS mean height (inches), error rate^A, and letter group for shortleaf pine seedlings.

Year	Treatment	Number of seedlings	LS Mean	Standard Error	Letter Group
2019	Fire	130	15.03	0.84	D
2020	Fire	95	17.33	0.84	CD ^B
2019	Herbicide	103	14.86	0.84	D
2020	Herbicide	74	20.44	0.84	C
2019	Control	52	28.05	2.07	B
2020	Control	37	63.50	2.07	A

A. Standard error rates are equivalent due to a balanced design of least square means among control, years, and treatment.

B. Different letters in the same column indicate significant differences (P=0.05).

Table 7. Year, treatment, number of seedlings, LS mean root collar diameter (inches), error rate^A, and letter group for shortleaf pine seedlings.

Year	Treatment	Number of seedlings	LS Mean	Standard Error	Letter Group
2019	Fire	130	0.21	0.02	CD ^B
2020	Fire	95	0.25	0.02	C
2019	Herbicide	103	0.2	0.02	D
2020	Herbicide	74	0.24	0.02	CD
2019	Control	52	0.6	0.04	B
2020	Control	37	1.22	0.04	A

A. Standard error rates are equivalent due to a balanced design of least square means among control, years, and treatment.

B. Different letters in the same column indicate significant differences (P=0.05).

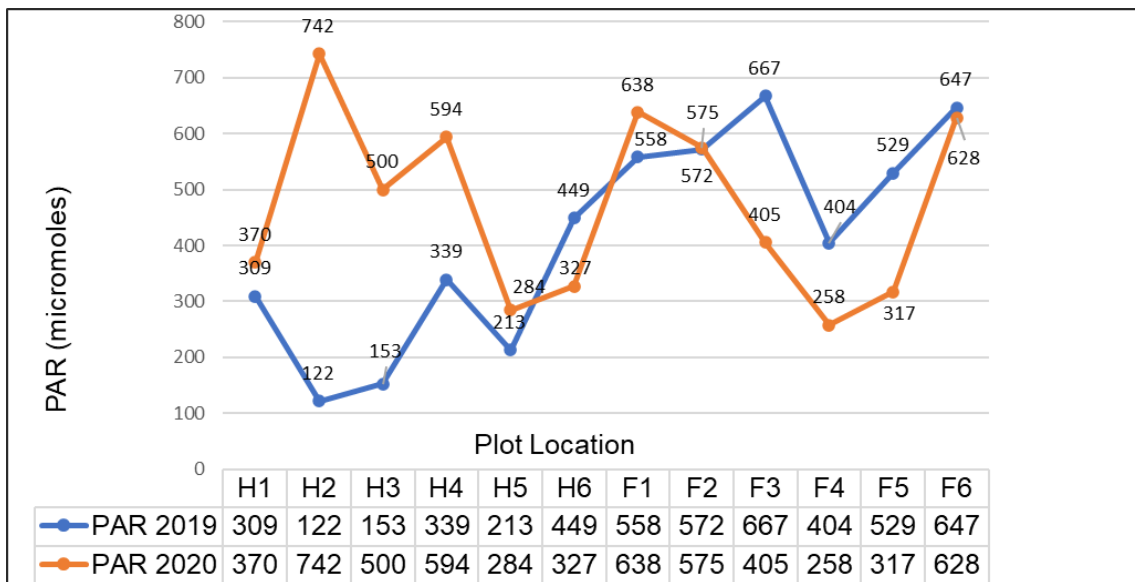


Figure 8. Average PAR measurements at plot locations for 2019 and 2020.

Chapter 6: Discussion

Survival Rate

The wildfire plots had a higher survival rate and were most likely influenced by the F1 plot which had a 95% survival rate. If the F1 plot was removed from the data group, the herbicide plots would have had a higher survival rate. Large, downed woody debris killed a noticeable amount of the shortleaf pine seedlings across all plots. Seedlings could have been killed or damaged by falling trees or limbs in either treatment, affecting survival percentages. Competition among the seedlings in the herbicide plots consisted of, primarily, chestnut oak seedlings that outnumbered the shortleaf pine seedlings a few hundred to one. In the wildfire plots, competition was comprised of herbaceous non-woody vegetation. Both forms of competition will have to be acknowledged and controlled if the shortleaf pine component is to establish itself as a dominant species in the stand.

Seedling Height

The 2020 herbicide plot seedlings grew taller than the 2020 burned seedling almost certainly due to the amount of tree mortality that was reached in the herbicide treatment plots. Although not statistically significant for the seedling height results, PAR values increased substantially (205 micromoles) in the herbicide plots from 2019 to 2020 compared to the fire plots where PAR values decreased (92 micromoles) from 2019 to 2020. This large increase in available light might explain the notable height growth achieved by the shortleaf pine seedlings in the herbicide plots. A similar study concerning shortleaf pine

plantation growth and yield in Tennessee, Alabama, and Georgia found that on plantations with a site index of 50, two-inch diameter seedlings after ten years had a yearly growth rate of 15.6-inches at 750 stems per acre (Smalley and Bailey, 1974).

Tree mortality did occur in the burn plots although mortality was scattered due to the erratic nature of the wildfire itself in its intensity and severity on the large diameter hardwoods. Fire intensity can be defined as the energy emitted during various stages of a wildfire, while fire severity can be defined as the impact of a fire on the ecosystem in which it is occurring (Keeley 2009). During the wildfire at Cumberland Forest, the temperature, reaction, and heating duration of the wildfire fluctuated as it traveled up or down slope and came into contact with vegetation of different sizes i.e., the fire intensity was erratic. As the fire came into contact with large diameter trees, some were immediately killed while others sustained mortal wounds for future mortality, and a few remained unharmed. This change in vegetation and environment as a result of the wildfire was the severity of the fire itself.

Also, soil scarification occurred in the wildfire plots giving non-woody, herbaceous competition the opportunity to be present in much larger quantities than in the herbicide plots. A study in northwestern Arkansas had similar results for controlling woody vegetation between fire and herbicides on upland

hardwoods and found that larger diameter hardwoods required an herbicide application rather than burning alone to control them (Montgomery et al., 2006).

Seedling Diameter

All treatment plots shared similarities except for the 2020 wildfire plots and the 2019 herbicide plots when compared against each other. This was due to the 2020 wildfire plot diameter measurements, which contained the largest mean root collar diameter at 0.25 inches; though this does not indicate importance due to the 2020 herbicide plots having a mean root collar diameter of 0.24 inches.

Though the PAR covariate had no significant effect on seedling root collar diameter, mean diameters in the herbicide plots were double of the root collar diameters in the fire plots from 2019 to 2020; this large gain coincided with the exponential growth in PAR values in the herbicide plots from 2019 to 2020. Further research in a more controlled growing environment could possibly help narrow down statistical differences in shortleaf pine seedling root collar diameters and their relation to different levels of photosynthetic active radiation.

Stand Predictions

The future composition of the stand can be hypothetically predicted based on if the stand is left alone or if forest management activities are further pursued. The overall goal of this study was to incorporate shortleaf pine back into an upland hardwood forest where it was once dominant and either approach will

result in a component of shortleaf pine with differences in stand density. Chestnut oak and red maple are the two species that influence these predictions.

The understory of the herbicide treatment plots consisted of white pine, sourwood, flowering dogwood, black oak, scarlet oak, white oak, sassafras, chestnut oak, American beech (*Fagus grandifolia*), red maple, pignut hickory (*Carya glabra*), mockernut hickory (*Carya tomentosa*), and tulip poplar. The vast majority of the understory at the herbicide plots consisted of chestnut oak. At the wildfire plots, the understory consisted of the aforementioned tree species with the addition of black locust (*Robinia pseudoacacia*).

Amongst the herbicide plots, oak regeneration, most particularly chestnut oak, was very dense across the forest floor. The imazapyr treatment on living oak stems was successful in causing their mortality but, with a site index of 55, equal to that of shortleaf pine, the site in general was a respectable location for chestnut oak germination and growth. As the canopy continues opening up, a release effect on the seedlings will gradually take place with the expectation of increasing vigorous growth (McQuilkin 1990). Without further management to control the oak regeneration, it will remain a prominent competitor to the shortleaf pine seedlings as the dominant tree species within the stand.

Another competitor to take note of is red maple. The imazapyr treatment killed most red maple stems as planned, but root sprouting accompanied by vigorous growth has taken place with sprouts reaching several feet in height. Furthermore, disturbances have been known to provoke red maple growth to the

point of an increase in stocking where it formerly transpired only as dispersed stems (Walters and Yawney 1990). Assumptions for the future stand composition in the herbicide area are that this will remain a hardwood dominated stand consisting mostly of red maple and oak spp., along with a temporary shortleaf pine component if further management activities are not employed.

Concerning the wildfire treatment area, there was a noticeable difference in seedling species composition. The herbicide treatment plots contained substantially more oak regeneration than the wildfire plots, which contained a considerable amount of sassafras seedlings, along with black locust seedlings that the herbicide plots lacked. The presence of so much sassafras can be attributed to the high severity of the burn that favors sassafras establishment through root sprouting (Sullivan 1993). The presence of so much black locust can be associated with the severity of the disturbance that lends itself to root sprouting of black locust (Huntley 1990). Though infrequent compared to the herbicide plots, red maple sprouting has occurred within the wildfire plots. Growth from the sprouts is generally sluggish and lack the vigorous development of the red maple sprouts found in the herbicide plots, making the wildfire study area an excellent candidate to promote shortleaf pine as the dominant species within the stand. Speculation for the future stand composition in the wildfire treatment area are that various oak spp., primarily chestnut oak, will dominate the stand with a temporary shortleaf pine component if further management activities are not utilized.

Management Implications

Incorporating a shortleaf pine component into an existing stand of hardwoods can be accomplished using a variety of silvicultural techniques. Even-age techniques such as a shelterwood cut or silvicultural clearcut are viable and are commonly, and historically, recommended first. On the other hand, un-even age techniques such as group or single tree selection can also be used to promote the natural ecology of a shortleaf pine dominated forest and are aesthetically preferable to a clearcut for most landowners (Jensen et al., 2007).

With the evident decline in natural shortleaf pine populations from land use changes, reduced disturbance events (South and Buckner, 2004), and the expansion of low-quality hardwoods, artificial regeneration is the likely candidate for the promotion of shortleaf pine in mature, upland hardwoods either by direct seeding or planting since a seed source is not available.

The advantages of direct seeding are that it can be done where planting is not a feasible option such as on harsh or difficult sites with rocks, stumps, or other physical barriers. It is essentially cheaper due to less labor and equipment costs than planting and large growing sites can be seeded more quickly with a limited time frame. There are, however, several disadvantages that come with direct seeding. Growth rates are no faster on trees from direct seeding so competing vegetation has an initially greater negative influence compared to planted trees. Seed predation must be controlled until germination takes place and sufficient moisture levels must be sufficiently maintained throughout the

germination cycle. Also, large quantities of seed, with the appropriate number of seed sources, must also be available. Planting provides a greater assurance of success due to much more control of the initial stages of seedling development from seed in a nursery setting thus, they are not exposed to the detrimental growth conditions seedlings from direct seeding are subjected to (Smith et al., 1996).

Once the decision has been made to artificially promote shortleaf pine regeneration in a closed canopied, hardwood forest, decisions over viable canopy removal treatments should be decided. Two treatments available to the landowner or manager are the use of prescribed fire and herbicide application.

For small, private landowners, large diameter hardwoods would most likely benefit from the use of herbicides for canopy removal. The erratic nature and variabilities associated with the use of burning can make its justification use more difficult. Furthermore, this study found that the use of herbicides killed larger diameter hardwood stems more quickly and efficiently than the use of fire alone where mortality could be extremely variable. These results were very similar to a study in the upland hardwoods of northwestern Arkansas that advocated the use of herbicides over burning alone in large diameter hardwoods (Montgomery et al., 2006).

Shortleaf pine restoration can be challenging because hardwood competition displays greater initial growth following canopy removal but greater shade tolerance with canopy retention compared to shortleaf pine (Kabrick et al., 2015).

Rather than one treatment alone, overstory and understory treatments should be considered (Olson and Olson 2016).

Chapter 7: Conclusions

Significant differences in survival rates between the two treatments were found. Wildfire plots had greater survival rates, though this was most likely the influence of a particular fire plot that had an abnormal survival rate of 95 percent (Objective 1).

Significant differences in height growth were found between treatments. The control contained the largest growth in height, followed by the herbicide plots (Objective 2).

Data results suggest no significant results were present for root collar diameter growth between wildfire and herbicide, though significant growth in root collar diameters were present at the control in full sunlight (Objective 3).

PAR values had no statistically significant effect on growth in seedling height and root collar diameter. Numerically, herbicide treated plots with PAR values that significantly increased from 2019 to 2020 also had a significant increase in height (Objective 4).

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Appendices

Appendix 1.

ANOVA table for shortleaf pine seedling survival

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
year	1	1	165.375	16.579	0.0006
trt	1	1	100.042	10.029	0.0048
year*trt	1	1	1.042	0.104	0.7499

ANOVA table for shortleaf pine seedling heights

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
trt	2	2	1548.385	180.933	<.0001
year	1	1	702.929	164.279	<.0001
year*trt	2	2	473.090	55.282	<.0001

ANOVA table for shortleaf pine seedling root collar diameters

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
year	1	1	0.173	379.301	<.0001
trt	2	2	0.856	939.821	<.0001
year*trt	2	2	0.152	166.894	<.0001

Vita

Max Street was born in Greeneville, Tennessee on October 30, 1990. In 2009, he graduated from Greeneville High School in Greeneville, TN and joined the Marine Corps.

After his term of enlistment in the military was completed, Max went to Walters State Community College in 2014 and then transferred to the University of Tennessee in 2015 as an undergraduate forestry student. He completed an internship in the summer of 2018 with the University of Tennessee Extension under the direction of Dr. Wayne Clatterbuck studying cherry bark oak. Max received a Bachelor of Science degree of forestry with a concentration in resource management in December 2018.

In January 2019, Max accepted a position as a graduate research assistant within the department of Forestry, Wildlife, & Fisheries at the University of Tennessee, Knoxville. While taking classes and teaching silviculture labs at UTK, he researched the recovery of shortleaf pine in upland, hardwood forests. His career goals include obtaining a position within a public land-based agency that focuses on silviculture, forest ecology, & forest management.