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Comparison of two planting stocks and two species for regenerating oak seedlings on Hurricane Katrina impacted sites

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Comparison of two planting stocks and two species for regenerating oak seedlings on
Hurricane Katrina impacted sites

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A Thesis
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Master of Science
in Forestry
in the Department of Forestry

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Many bottomland hardwood stands in southern Mississippi lacked management prior to Hurricane Katrina. Following removal of overstory oaks, no seed source was available to naturally regenerate these stands. Artificial regeneration became the most viable option, but information was lacking on how to successfully reestablish thousands of acres of bottomland forests quickly and successfully.

Bareroot and conventional containerized seedlings of Nuttall oak (*Quercus texana*) and swamp chestnut oak (*Quercus michauxii*) were planted on two sites in southern Mississippi. After two growing seasons Nuttall oak exhibited similar survival to (93.4%), better groundline diameter growth (13.0 mm) than, and better height growth (68.8 cm) than swamp chestnut oak (92.5%, 6.6 mm, 43.9 cm, respectively). Bareroot seedlings had the highest survival (94.5%), best groundline diameter growth (10.3 mm), and best height growth (66.6 cm), though conventional containerized seedling survival (91.4%), groundline diameter growth (9.3 mm), and height growth (46.0 cm) were all acceptable. Considering seedling cost and overall performance, bareroot seedlings provide the most effective option for artificial regeneration on high quality bottomland hardwood sites.

DEDICATION

I dedicate this thesis to my wife, Emilee, for the love and support she has shown me, especially in our time in Starkville. There is no way I would have had the motivation or courage to attend Mississippi State and move so far from home had you not supported me the entire way.

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CHAPTER I

INTRODUCTION

Hurricane season in the southeastern United States can begin as early as May and last well into December. The peak of hurricane season is often from the middle of September until the end of October, with the largest and most devastating hurricanes often formed within this time period (Wamsley 2018). These storms bring winds ranging in speeds from 119 kilometers per hour (km/h) to in excess of 280 km/h, as well as heavy rainfall and potential flooding (Wall 2011; Godlewski 2018). Hurricane season is of utmost importance to coastal states due to the potential for damage and economic losses associated with it.

Publicized damage from hurricanes is often of homes and large cities, but southern forests do not escape negative impact. This includes both pine and hardwood forests. Straight line winds associated with hurricanes can topple large oaks (*Quercus spp.*), especially when their root systems are in saturated soils due to the precipitation associated with these storms (Oswalt et al. 2008). These oaks play a key role in coastal ecosystems of the Southeast. Various species of wildlife are closely associated with oaks and depend on them for food and cover (McShea and Healy 2002; Gardiner et al. 2010). Oaks also play a major part in the economics of the region, due to their value in lumber, flooring, cross ties, and pulpwood (Luppold and Jacobsen 1985). They also provide important ecosystem services, including development and preservation of soil, air filtration and oxygen production, rainfall interception, and runoff control. Large oaks also

provide aesthetic benefits and can increase property value (Ulrich et al. 1991; Kuo et al. 1998). By destroying these trees, hurricanes alter the landscape and reduce benefits provided by oaks.

Oaks are typically grown on longer rotations than other merchantable species, so the possibility of a damaging incident is increased due to the longer time frame. Any number of catastrophic events can occur over a prolonged time period, including natural disasters such as hurricanes. These events can have severe economic impacts on forest landowners. Extensive research has been conducted on various regeneration methods of southern hardwoods including growth rates, survival rates, and costs associated with each, yet knowledge on growth and survival of alternate planting stocks for oak regeneration is still lacking.

Mississippi is one of the coastal states and has received numerous impacts from hurricanes over the years. On August 29, 2005, Hurricane Katrina made landfall on the Gulf Coast of the United States, including Mississippi, as a Category Three hurricane with wind speeds up to 280 km/h (Blake et al. 2011; Wall 2011). This storm left an abundance of damage in its wake. According to Oswalt et al. (2008), approximately 54 million trees in Mississippi were destroyed. The United States Forest Service (2005) estimated that forty percent of the damage occurred in hardwood forests. This magnitude of damage called for quick and effective regeneration of these hardwoods, primarily of oak species. It is well known that oak regeneration can be a complicated process, even when carefully precontrived (Loftis and McGee 1993; Cook et al. 1998; Dey 2014). Due to the complexity of natural regeneration (Ezell et al. 1999; Peairs et al. 2004) and mass removal of an overstory seed source, artificial regeneration is viewed as the best option following vast damage caused by a hurricane.

Artificial regeneration is defined by the United States Forest Service (2018) as “renewal of the forest by planting or direct seeding; establishing a new stand of trees by planting seeds or

seedlings by hand or machine.” It is worth noting that costs associated with successfully artificially regenerating large areas in oak can be substantial. Artificial regeneration following a disaster such as a hurricane would require extensive site preparation to remove woody biomass left behind. Even if a salvage harvest could be conducted, profits returned by such a harvest would be substantially less than returns gained by a traditional timber harvest, and this salvage harvest revenue may not be enough to cover the cost of artificially regenerating oaks. Many landowners whose oak forests were destroyed by Hurricane Katrina needed a cost effective and reliable means of artificially regenerating their land.

Regeneration of high-quality hardwoods has been a recurring issue in southern forest management. High survival rates of artificially regenerated oak seedlings are of the utmost importance regarding long-term establishment of an oak dominated forest. Bareroot seedlings are the most common means of artificial oak regeneration in the southeastern United States. Containerized seedlings make up only 0.3% of annual plantings of oak seedlings (Dey et al. 2008). Regardless of planting stock, survival and future productivity of these stands can be improved using common forest management practices, including proper site preparation and herbaceous weed control (Dey et al. 2008).

The in-depth planning and costs required for successful artificial oak regeneration have led many landowners to consider other “less complicated” species, such as Loblolly pine (*Pinus taeda*) when reforesting damaged lands. They turn to quicker growing, seemingly more economical options (Dey et al. 2008). This change in land use caused by establishing non-oak species on what was previously oak forestland, will likely not provide landowners or the ecosystem with services that an oak dominated forest can provide. For this reason, it is highly

important that landowners be provided with pertinent information regarding effective means of establishing oak forests following natural disasters in an economically viable manner.

The overall goal of this research is to generate information and beneficial knowledge regarding oak establishment following a natural disaster in which the seed source component of a stand was removed prior to adequate natural regeneration being established. This project will produce information as to which planting stock (bareroot or containerized) will be the most successful in establishing an oak forest. This will allow landowners to make more educated decisions regarding management of their land.

Objectives

The primary goal of this research project is to compare the two-year performance of two different planting stocks of two oak species on sites impacted by Hurricane Katrina.

Objectives are as follows:

- I. Compare the two-year survival, height growth, and groundline diameter growth of two oak species:
 - A. Nuttall Oak (*Quercus texana*)
 - B. swamp chestnut oak (*Quercus michauxii*).
- II. Compare the two-year survival, height, and groundline diameter growth of two planting stocks:
 - A. High quality 1-0, bareroot seedlings
 - B. Conventional containerized seedlings

Hypotheses

- I. Nuttall oak seedling survival, height growth, and groundline diameter growth will be equal to that of swamp chestnut oak seedlings.
- II. Bareroot seedling survival, height growth, and groundline diameter growth will be equal to that of conventional containerized seedlings.

CHAPTER II

LITERATURE REVIEW

Hurricane Katrina

Hurricane Katrina left in its wake billions of dollars in damages and as many as five million acres of damaged forestland across parts of Louisiana, Mississippi, and Alabama (Chambers et al. 2007; Cook-Anderson 2007). Winds of over 280 kilometers per hour devastated approximately 20 percent of timber within the path of the storm. Damage to trees ranged from minor branch breakage to severe trunk twisting or windthrow, with 521 million trees receiving some form of damage and 54 million trees being completely destroyed within Mississippi (Cook-Anderson 2007; Oswald et al. 2008). This damage occurred primarily within 60 miles of the coast (United States Forest Service 2005).

Oak Regeneration

Oak regeneration is a popular objective among private landowners in the southeastern United States, whether it be for production, recreation, or aesthetic purposes (Rousseau 2008; Rousseau 2015). Oaks are used for furniture, barrels, lumber, flooring, and railroad ties. Tannins found in the bark of oak trees are used to prepare leather. Historically, oak was used in ship making, and Native Americans ground acorns into a type of flour for human consumption (Rousseau 2015).

Unfortunately, numerous species of oak possess wide ranges of site requirements and differing growth habits. This makes regeneration of oaks, especially bottomland adapted species, difficult. When oaks are managed in a typical forest setting, barring events such as a hurricane, a seed source may be available from overstory trees at all times (Clatterbuck and Meadows 1992), and can be used for natural regeneration methods such as group selection and shelterwood harvests (Cunningham 2015; Rousseau 2015). When large quantities of overstory trees are removed in a single event prior to allowing advanced natural regeneration to occur, as was the case with Hurricane Katrina, natural regeneration becomes challenging or impossible. This is due to seed source removal and lack of well-developed seedlings. Land managers must turn to artificial regeneration in these scenarios if an oak forest is the desired outcome.

Artificial Regeneration

Artificial regeneration has been a common practice in pine management for decades, whereas its use in oak management has been less frequent. This can be attributed to the cost of establishing an oak dominated stand, as well as the extended rotation length (Rousseau 2015; Rousseau 2017a). Adequate site preparation, high quality seedlings, proper planting, and competition control are necessary when establishing a successful oak stand using artificial regeneration (Dey et al. 2008; Rousseau 2015). Success may be defined as having a desirable proportion of planted oaks reach dominant or codominant status in the stand (Dey et al. 2008). While many past artificial regeneration efforts in hardwoods planted only approximately 300 trees per acre, an early indication of future success for a stand is having at least 400 oak seedlings per acre at the end of the first growing season (Rousseau 2015).

Planting oak seedlings in bottomlands is a reliable method of reforestation when done correctly, and the probability of establishing a healthy oak stand is high. In addition to selecting appropriate species for a site, high quality seedlings must be obtained, proper care must be given to the seedlings prior to planting, and proper planting techniques must be employed. Seedling provenance should be from a location similar to the planting site to ensure that particular seedling has adaptations to suite the planting environment (Cullina 2002).

Bareroot Seedlings

Most seedlings produced at forestry nurseries are bareroot seedlings. Bareroot seedlings are advantageous for several reasons. They are less expensive than containerized seedlings, easier to transport, and easier to plant (Kennedy 1992; Bassuk 2000; Grossnickle and El-Kassaby 2015). Bareroot oak seedlings should have at least 50 centimeters (cm) of stem above the root collar and a root collar diameter of at least one centimeter (Kennedy 1992; Jacobs et al. 2005; Rousseau 2015). Seedlings meeting these requirements have demonstrated an ability to overcome transplanting shock and become established before they are overtopped by competing vegetation (Jacobs et al. 2005).

Kennedy (1992) and Davis and Jacobs (2005) stated that roots should be well developed. Gould and Harrington (2009) also recognized the benefits of fibrous root systems in bareroot seedlings. Current specifications maintain the height requirement stated by Kennedy (1992) but add a minimum of 10 first order lateral roots (FOLR) (Kormanik et al. 1995; Thompson and Schultz 1995; Kormanik et al. 2002; Davis and Jacobs 2005; Rousseau 2015; Ezell 2019). Kormanik et al. (1995) found that individual seedlings with low numbers of FOLR (less than 10) became suppressed and could not compete with the growth and survival of seedlings with higher

numbers of FOLR (10 or more). Thompson and Schultz (1995) reported a significant relationship between the number of FOLR at the time of planting and height, diameter growth, and survival of planted oak seedlings (Dey et al. 2008).

Previous studies in the same series as this research have revealed bareroot seedlings to maintain the highest survival of any planting stock (Hollis 2011; Conrad 2013; Dowdy 2015; Reeves 2016; Durbin 2018; and Miles 2019) after two growing seasons. These studies cover a wide range of species including, the two focus species of this study (Nuttall oak and swamp chestnut oak). Study sites in the earlier works of this series are variable, though all were in stream bottom sites.

Alkire (2011) found that after one growing season, bareroot oak seedlings displayed greater height growth when compared to conventional containerized seedlings. Similar studies by Hollis (2011), Conrad (2013), Reeves (2016), and Durbin (2018), found that after two growing seasons bareroot seedlings displayed superior height growth compared to conventional containerized oak seedlings.

Bareroot seedlings have also been found to be top performers in groundline diameter (GLD) growth. Alkire (2011) found that after one growing season, bareroot oak seedlings had the greatest GLD growth. Similarly, after two growing seasons, Durbin (2018) found that bareroot oak seedlings outperformed other planting stocks regarding GLD growth.

Hollis (2011), Alkire (2011), Conrad (2013), Dowdy (2015), Reeves (2016), Hall (2017), Durbin (2018), Miles (2019), and Gentry (2020) all concluded that high quality 1-0 bareroot seedlings can properly reforest lands when paired with proper site preparation, seedling care, quality planting, and first year herbaceous weed control. Such operations are of much lower cost compared to that of conventional containerized seedlings.

Storage and Handling

Bareroot seedlings have roots that are vulnerable to various forms of damage, but damage can be prevented when seedlings are handled and cared for appropriately. Seedlings should be stored in a cool, moist, and shaded environment until planting (Kushla and Ezell 2017). A cold-storage unit is preferable but, as long as roots do not become dry or freeze a barn, shed, or dense shade will suffice. Care should be taken to ensure roots remain moist at all times (Kennedy 1992; Kushla and Ezell 2017). Seedlings should be watered within their storage bag every two to three days if extended storage is necessary (Kushla and Ezell 2017). During transport of seedlings, bags should be covered to prevent excessive drying and wind damage (Ezell 2019).

For planting, seedlings should be transferred from storage bags to a bucket or planting bag where their roots will not be exposed (Kennedy 1992; Bassuk 2000). Exposure time during this transfer should be minimized to decrease desiccation and damage of the root system. Mud or water can be used to prevent drying within the planting bag (Kushla and Ezell 2017). Care should be taken not to break stems, branches, or roots of the seedling (Bassuk 2000).

Planting

Bareroot oak seedlings are best planted between the months of January and March while the seedlings are dormant. Recommended spacing for timber production is 3 by 3 meters (m) or 3.6 by 3.6 meters (Kennedy 1992; Rousseau 2015). Wildlife oriented management plans may call for wider spacing to meet objectives, (Kennedy 1992). However, these wider spaced planting are cause for concern in regard to wood quality due to lack of self-pruning, as well as stand stratification.

Seedlings can be planted using dibble bars or planting shovels (Kushla and Ezell 2017). When using such tools, planting slits should be closed from the bottom up. This forces air at the

bottom of the slit upward and out of the hole, preventing air pockets which can cause roots to dry out and die (Kushla and Ezell 2017). Roots should be straightened before placing them in the ground to allow for better development (Kennedy 1992). It is also imperative that the hole be deep enough to prevent “J-rooting.” Planting depth should allow for the root collar to be placed just below the soil surface without forcing any bend to the roots (Kennedy 1992; Bassuk 2000).

Containerized Seedlings

Containerized seedlings are generally grown inside a green house or shade house in containers ranging in sizes from a few cubic cm to several liters. Containerized seedlings are significantly more expensive than bareroot seedlings (Jacobs 2003; Humphrey et al. 1993). In recent years, smaller containerized seedlings have become more widely available. Their higher price, when compared to bareroot seedlings, stills deters wide utilization (Dey et al. 2008).

It is imperative that containerized seedlings be obtained from nurseries which are knowledgeable on the proper care of seedlings. Improper care at the nursery can result in mass mortality in the field (Reeves et al. 2016; Miles 2019; Gentry 2020). A common cause of such mortality is freeze damage which occurs when containerized seedlings are not properly protected from the elements. In a study conducted by Reeves et al. (2016), 99.8 percent mortality of conventional containerized was observed at the first survival check post-planting. This mass mortality was attributed to below-average freezing temperatures in January, when trees were still in the nursery. These comparatively extreme periods of freezing temperatures resulted in roots freezing and dying. Evidence of nursery damage may not be apparent until seedlings are supposed to break dormancy. Prior to that, freeze-killed seedlings appear healthy in casual observation (Reeves et al. 2016). Miles (2019) and Gentry (2020) also attributed poor

conventional containerized seedling survival and growth performance to unusually low winter temperatures prior to planting. The authors concluded that the nursery from which the seedlings were obtained had not sufficiently protected them from these conditions. Miles (2019) witnessed low survival rates as early as April, with survival rates steadily declining over the duration of the first growing season. Gentry (2020) observed low survival rates as early as May, and survival rates continued to fall through the end of the growing season.

Despite these findings, containerized seedlings can be advantageous for several reasons (Dey et al. 2008). In clear-cut stands, conventional containerized seedlings have demonstrated superior growth and higher success probabilities. Taller seedlings have less risk of having terminal buds browsed by deer, or having their crowns inundated during floods. The greater height of larger containerized seedlings also promotes better competition with other vegetation for light. Conventional containerized seedlings may improve regeneration success on harsh sites which may be nutrient or water limited. This is due to an intact ball of soil remaining around the roots (Dey et al. 2008). Containerized seedlings may also allow for an extended planting season by allowing for seedling to be planted later in the winter or even early spring (Brissette et al. 1991).

Studies conducted at Mississippi State University have revealed that containerized seedlings outperform bareroot seedlings in some scenarios. Conventional containerized seedlings had the greatest survival among three planting stocks in two different studies (Alkire 2011; Dowdy 2015). Additionally, greater groundline diameter (GLD) and height growth of conventional containerized seedlings was witnessed in two studies (Conrad 2013; Dowdy 2015). Hall (2017) found that containerized seedling height growth was the largest, though the difference was not significant compared to bareroot seedling height growth after the first two

growing seasons. Miles (2019) found that conventional containerized seedlings displayed the greatest height growth of three planting stocks studied.

Nuttall Oak

Nuttall oak (*Quercus texana* Buckley) grows on bottomland sites along the Gulf Coastal Plain from Florida to southeastern Texas and north along the Mississippi River Alluvial Valley into Missouri and Tennessee. The species thrives on poorly drained, heavy alluvial clays, which are common in the first bottoms of the Mississippi Delta (Burns and Honkala 1990; Rousseau 2004). These soils are often on flats that can be covered with 8 to 20 cm of water throughout the winter (Burns and Honkala 1990). Nuttall oak is not commonly found in permanent swamps and prefers a soil pH range of 4.5 to 6.5 (MossyOak Nativ Nurseries 1, 2020). Nuttall oak grows primarily on soils in the orders of Inceptisol and Entisol orders (Burns and Honkala 1990).

Nuttall oak is intolerant of shade and seedlings are known to survive and grow quickly in openings. Sites with shallow water tables often display superior growth (Burns and Honkala 1990). Growth of Nuttall oak can be rapid, especially in early years with groundline diameter growth of 10 cm in 10 years being common and 20 cm possible. Groundline diameter growth can be used as a predictor for overall health and development of the belowground root system. Rapid groundline diameter growth at a young age allows for shoot development to occur earlier as well, due to the large root system being able to support aboveground biomass. This rapid early growth is likely due to an adaption of Nuttall oak to resist inundation for extended periods, which can be common in its natural habitat (Reeves et al. 2016).

In the series of studies in which this study falls, Nuttall oak has been planted in five prior iterations. Regardless of other oak species in those studies, Nuttall oak had as high or higher

survival rates (Hollis 2011; Alkire 2011; Conrad 2013; Reeves 2016; and Hall 2017). Nuttall oak also displayed the highest GLD growth of the studied species in all five studies (Hollis 2011; Alkire 2011; Conrad 2013; Reeves 2016; and Hall 2017). Four out of the five studies found that Nuttall oak also outperformed its counterpart in height growth (Hollis 2011; Alkire 2011; Reeves 2016; and Hall 2017).

Swamp Chestnut Oak

Swamp chestnut (*Quercus michauxii* Nutt.) oak grows along the Atlantic Coastal Plain from eastern Pennsylvania to northern Florida, and westward to east Texas. The species extends north along the Mississippi River Alluvial Valley into southern Illinois and Indiana. The species is widely distributed on well drained, loamy, first-bottom ridges and is principally found on well drained silty clay and loamy terraces in bottoms associated with rivers and streams (Burns and Honkala 1990; Rousseau 2004). Soils such as these are found primarily in the Alfisol and Inceptisol orders (Burns and Honkala 1990). Swamp chestnut oak prefer a soil pH range between 4.5 and 6.5 (MossyOak Nativ Nurseries 2, 2020).

Swamp chestnut oak is intolerant of shade and seedlings require openings for establishment (Burns and Honkala 1990). The species can tolerate growing season flooding, but only for short periods of time (Ross 2013). Overall survival and growth of individual seedlings is greatly influenced by microsite. Slow height growth of less than 10 cm per year is common (Hook 1969; Burns and Honkala 1990; Ross 2013). Soil drainage has the largest impact on height growth during the first year, with well drained soils producing superior height growth over poorly drained soils. However, over a two-year period, soil type has the largest impact on height growth, with soil drainage having little effect (Hook 1969; Burns and Honkala 1990). This

suggests drainage is more important to establishment than to subsequent growth. Even under ideal conditions, swamp chestnut oak is considered a slow growing species, growing as little as five cm in height the first year and 10 cm the second (Hook 1969).

In the series of studies in which this study falls, swamp chestnut oak has been planted in three prior iterations. Of these three studies, swamp chestnut oak survival was as high as or higher than the other oak species utilized (Hollis 2011; Dowdy 2015; Durbin 2018). Durbin (2018) found that swamp chestnut oak outperformed Shumard oak (*Quercus shumardii* Buckley) in GLD growth, while Dowdy (2015) noted that swamp chestnut oak displayed greater height growth than water oak (*Quercus nigra* L.). It should be noted that Hollis (2011) stated that swamp chestnut oak was outperformed by Nuttall oak, which is known as a prime regenerative species due to its high survivability and outstanding growth.

Herbaceous Weed Control

Herbaceous Weed Control in Oak Plantations

Herbaceous competition poses the greatest threat to oak seedlings during early years of establishment due to extensive root systems which can outcompete young oak seedlings for water and nutrients (Self et al. 2014). Herbicide applications can control herbaceous competition when applied correctly. This increases growth of crop trees and reduces mortality (Ezell et al. 2007; Ezell and Self 2017). Herbicide application can also potentially reduce vole herbivory on planted oak seedlings (Self 2016). Herbaceous weed control (HWC) is prudent when establishing oaks, as poor growth and survival is common in oak plantations which lack HWC.

It is imperative that the most effective herbicide or tank mix be chosen based on target species and site constraints, and the application should occur at the most effective time (Miller

1992; Kochenderfer et al. 2012). Thus, competing vegetation on a site should be identified to aid in selection of a herbicide which will maximize competition control. Each herbicide has its own guidelines to ensure safe and effective control, and herbicide labels should be read carefully and followed.

Control can be accomplished using broadcast, band, or spot applications. Band applications are slightly less expensive than broadcast treatments, but reinvasion of undesirable species from untreated areas can occur. Band application is also only applicable when planting rows are well defined and are most often applied by hand but can also be applied from a tractor or ATV (Miller 1992; Seifert et al. 2007).

Competition control improves growing conditions for planted oak seedlings. Liechty et al. (2017) found that moisture in the surface layer of soil surrounding oak seedlings was significantly higher when areas were intensively treated with HWC, as compared to areas where seedlings were not treated. The soil moisture difference was magnified during drier months of the growing season, as soil surrounding seedlings in treated areas was able to retain more moisture. During growing seasons when drought stress is severe, this higher soil moisture content following HWC is likely to increase survival rates for planted oak seedlings (Liechty et al. 2017).

Timing of Application

Herbicide performance is maximized when target plants are most susceptible. Application should also take place when crop trees are the most resistant to injury (Miller and Bishop 1989). Applying herbicide too early or too late reduces or eliminates effectiveness and could damage the crop tree (Miller 1992). Depending on the herbicide to be used, either pre-

emergent or post-emergent timing of application is important (DuPont 2006). Pre-emergent and post-emergent refers to emergence of target vegetation and is determined by the specific herbicide in use. It is also of utmost importance to apply herbicide under appropriate weather conditions, as dictated by the herbicide label (DuPont 2006).

Effectiveness of Oust XP® in Young Oak Plantations

Oust® XP (sulfometuron methyl) has been established as the preferred treatment for HWC in most hardwood species for over twenty years (Ezell and Catchot 1998). Oust® XP is labeled for HWC at 70-240 grams/hectare (g/ha), to be applied after transplanting. Oust® XP is best applied as a pre-emergent herbicide, before weeds sprout, and is not recommended for use on poorly drained or marshy sites, unless seedlings have been planted on beds (DuPont 2006). Application should take place before seedlings break dormancy (bud swell stage) and leaf out (DuPont 2006). Common practice is to apply Oust® XP prior to bud break, between February and March (Ezell and Self 2017). Injury can occur when bud break has already taken place (Miller 1992).

Numerous screening studies have identified Oust® XP as an effective control for herbaceous weeds when planting oaks (Koslinki and Holt 1985; Wright and Holt 1985; Seifert 1989; Self et al. 2014). Oust® XP provides excellent weed control and minimal damage to various oak species (Seifert 1989). Oust® XP is effective at controlling a wide array of grasses and forbs that are often competitive with young oak seedlings (DuPont 2006; Ezell and Self 2017). While very effective, Oust® XP does not control all competitors to oak seedlings (Miller 1992; DuPont 2006).

Oust® XP has been observed to increase survival in young oak plantations. Studies show that 140.1 grams/hectare pre-emergent application of Oust® XP was effective at controlling herbaceous competition and improved overall survival of oak seedlings by 21 to 44 percent (Ezell et al. 2007). In other studies, Oust® XP proved effective in boosting first year survival of oak seedlings by 20 percent (Ezell and Catchot 1998), and it improved survival in the second year for Shumard oak seedlings (Hodges and Ezell 2001).

Specifically, in Nuttall oak and swamp chestnut oak establishment, Self et al. (2014) found that survival was maximized by Oust® XP applications during the initial growing season alone. Swamp chestnut oak seedling heights were significantly lower in areas receiving two years of Oust XP® application compared to a one-year application. However, this is not believed to be directly influenced by the application itself and was attributed to variations among micro-sites, leaf scorching, and soil desiccation. The lack of significant increase in growth or survival, paired with the extra cost of application for two years, would encourage Oust® XP as a first-year application only (Self et al. 2014). In direct control of oak seedling competitors on sites damaged by Hurricane Katrina, Ezell and Self (2017) found Oust® XP more effective at controlling herbaceous cover, when compared to other common herbicides and mixes.

CHAPTER III

MATERIALS AND METHODS

Site Location

Two separate, privately owned sites in southern Mississippi were utilized in this study. The Carney site was approximately 20.9 kilometers south of Columbia, Mississippi (31° 6' 6.3007" N, 89° 49' 54.7698" W). The Malone site was approximately 25.8 kilometers west of Hattiesburg, Mississippi (31° 23' 17.2342" N, 89° 28' 3.927" W). These coordinates correspond with the initial corners of establishment of each site, shown in Figures 3.1 and 3.2, respectively

Design of the Study

Each site had a randomized complete block (RCB) design with three replications of each treatment with treatment defined as each planting stock/species combination (Table 3.1). Each replication contained 100 seedlings per treatment. This resulted in 400 seedlings per replication and 1,200 seedlings per site.

Planting order was randomly determined for the four treatments. Treatments were then assigned a unique color. These colors correspond with the color pin flags each seedling was marked with, for ease of treatment identification (Table 3.1).

Table 3.1 Planting stock/species combination and the associated color code for each combination.

Planting Stock	Species	Color Code
Bareroot	Nuttall Oak (<i>Quercus texana</i>)	Red
Bareroot	swamp chestnut oak (<i>Quercus michauxii</i>)	Blue
Containerized	Nuttall Oak (<i>Quercus texana</i>)	Orange
Containerized	swamp chestnut oak (<i>Quercus michauxii</i>)	Yellow

- 1-0 bareroot Nuttall oak seedlings will henceforth be referred to as bareroot Nuttall oak.
- 1-0 bareroot swamp chestnut oak seedlings will henceforth be referred to as bareroot swamp chestnut oak.
- Conventional containerized Nuttall oak seedlings will henceforth be referred to as containerized Nuttall oak.
- Conventional containerized swamp chestnut oak seedlings will henceforth be referred to as containerized swamp chestnut oak.

Study Area Delineation

In November 2018, both sites were laid out in preparation for planting. The owner of the Malone site requested that a 6.1-meter-wide road be left unplanted across the study area. For this reason, length of the Malone site was slightly greater than that of the Carney site. The Malone site measured 65.8 meters in width by 117.7 meters in length, including the width of the road. This encompassed an area 0.77 hectares in size. The Carney site measured 65.8 meters in width by 111.6 meters in length. This encompassed an area 0.73 hectares in size.

An initial corner was established (southeast corner for the Malone site, northeast corner for the Carney site) and subsequent corners were established based off of length and direction

from the initial corner (Figure 3.1, Figure 3.2). A Lufkin® 91-meter measuring tape was used to measure distance and a Silva® compass was used to measure angles. Corners of the study area were checked for square by compass measurement, with all opposite boundary lines parallel, to ensure seedlings could be planted at an even spacing, in straight rows.

Based on study area dimensions, it was determined that seedlings could be planted at a spacing of 1.8 meters between rows and 2.1 meters between trees on rows. This would allow each treatment within a replication to be comprised of two rows, with 50 seedlings per row (Figure 3.1, Figure 3.2). This resulted in twelve rows of seedlings per replication and 36 rows on each site. Blocks were placed perpendicular to slight topographic changes present on both sites, to maximize variation in data among replications.

Rows were marked every 1.8 meters using rebar. Rebar were flagged, in pairs, using the color corresponding to the treatment planted on that row. Aluminum tags with replication, planting stock, and species information for each row were attached to each rebar to aid in quick future assessment of seedlings. Rebar at the end of rows were also tagged using aluminum tags containing similar information.

Once beginning and end rebar were established and flagged, pin flags were placed every 2.1 meters along the length of the row. Pin flag color corresponds to flagging color on rebar as well as the color assigned to each treatment (ex. a rebar flagged with orange flagging had 50 orange pin flags along its length, and this row was planted in containerized Nuttall oak seedlings—refer to Table 3.1, Figures 3.1 and 3.2.)

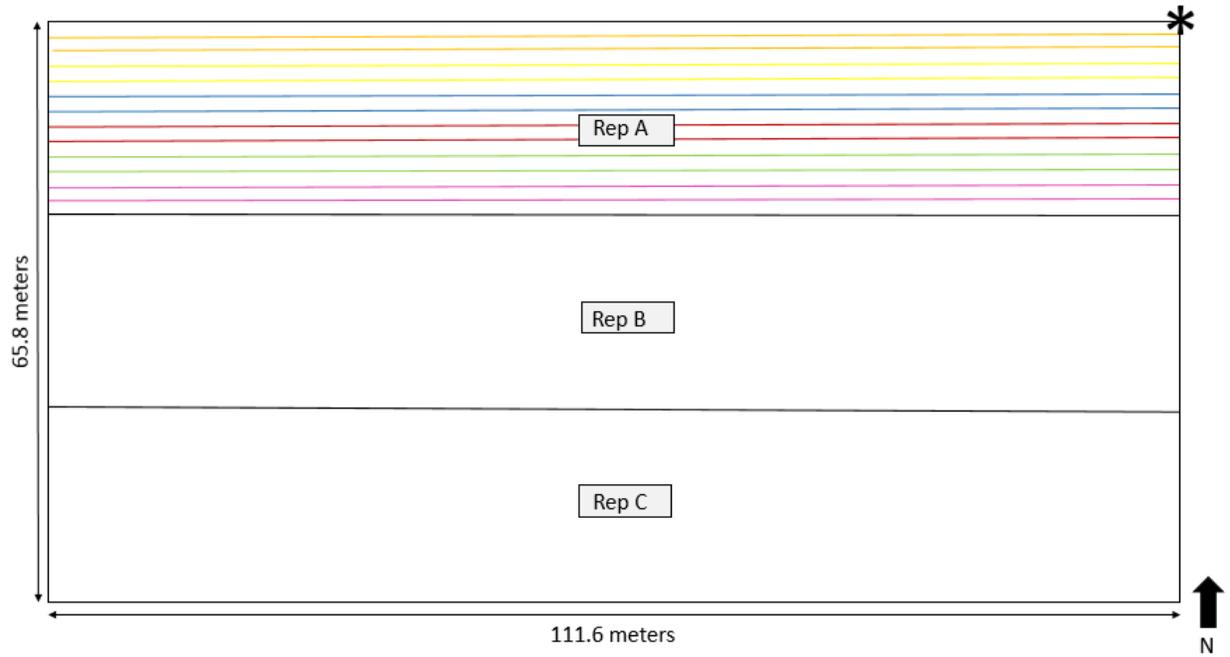


Figure 3.1 Site schematic for Carney site.

*Asterisk shows initial corner for study site establishment. Pink and green planting rows not utilized in this study.

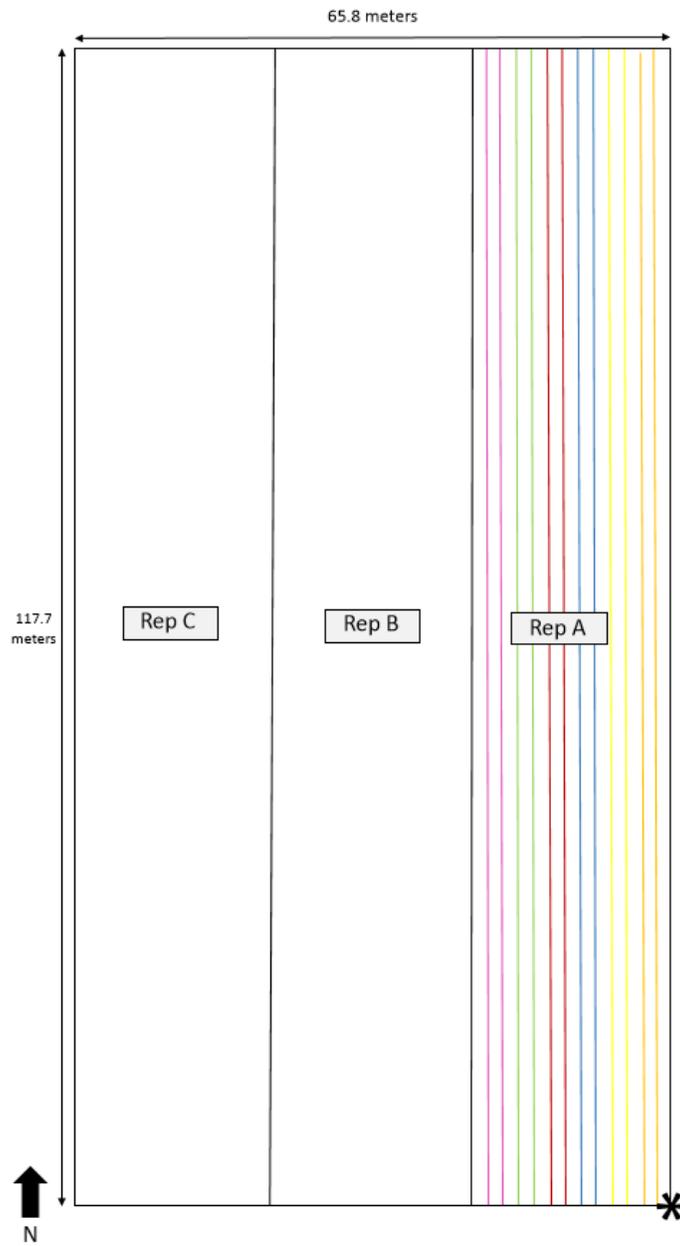


Figure 3.2 Site schematic for Malone site.

*Asterisk shows initial corner for study site establishment. Pink and green planting rows not utilized in this study.

Seedling Establishment

On February 7, 2019, 1,000 bareroot swamp chestnut oak seedlings and 1,000 bareroot Nuttall oak seedlings were obtained from ArborGen Nursery in Bluff City, Arkansas. These seedlings cost approximately \$0.25 per seedling. Six hundred containerized swamp chestnut oak seedlings and 600 containerized Nuttall oak seedlings were obtained from Mossy Oak Nativ Nurseries in West Point, Mississippi on the same day. These containerized seedlings cost approximately \$2.00 per seedling. Both bareroot and containerized seedlings were handled carefully and stored in a cool, dark, and moist location until planting.

Seedlings were hand planted using planting shovels and correct planting technique on February 9, 2019. Seedling spacing was 1.8 meters by 2.1 meters. According to USDA Web Soil Survey (2018), both sites are well suited for hand planting seedlings. Bareroot seedlings were carefully checked prior to planting to ensure good quality, with culling used to ensure that only the highest quality seedlings were used in this study. Seedlings were culled in the field based off lack of first order lateral roots (FOLR) and overall stem health. Seedlings with less than 10 first order lateral roots or a damaged stem were discarded. Culling of seedlings was left up to individual tree planters. Seedlings were planted adjacent to pin flags in each row. Pin flags were then relocated directly beside the stem of the seedling to facilitate locating them in the future.

Soil Sampling and Soil Characteristics

Soil samples were taken in December 2018 for analysis by the Mississippi State University Soil Testing Lab. Samples were taken from the top 30 cm at 10 locations across each site. Samples were mixed by site and submitted for analysis of nutrient availability, pH, texture, and organic matter content.

According to USDA Web Soil Survey (2018), the Carney site was composed of about 50 percent frequently flooded Bibb silt loam soil and 50 percent Stough fine sandy loam with zero to two percent slopes. The USDA Web Soil Survey also stated that potential for seedling mortality on the Carney site was high. Analysis by the Mississippi State University Soil Testing Lab revealed that the Carney site's soil was approximately four percent clay, 28 percent silt, 68 percent sand and best described as a sandy loam (Table 4.8). The pH was 5.2 and organic matter content was 2.5 percent, with a 6.7 cation exchange capacity (CEC) (Table 4.8). An in-depth description of nutrient availability is presented in Table 4.9.

According to USDA Web Soil Survey (2018), the Malone site was composed of primarily (approximately 85 percent) Falkner silt loam soil, with two to five percent slopes. The additional 15 percent of this site was composed of Freestone, Susquehanna, and Prentiss soils, with five to 12 percent slopes. The USDA Web Soil Survey also stated that potential for seedling mortality on the Malone site was low. Analysis by the Mississippi State University Soil Testing Lab revealed that the Malone site's soil is approximately 3 percent clay, 64 percent silt, 33 percent sand and best described as a silt loam (Table 4.8). The pH is 5.7 and organic matter content is 2.4 percent, with a 6.1 cation exchange capacity (CEC) (Table 4.8). An in-depth description of nutrient availability is presented in Table 4.9.

Precipitation Data

Rainfall data were collected at both sites using a Rainwise tipping bucket gauge in combination with a Hobo Pendant data logger. This gauge was mounted on a post above ground vegetation and away from any overhead obstruction that could influence rainfall collection. Data were uploaded to a laptop in the field using HOBOWare Plus Software. Monthly rainfall data

were assessed for the 2019 growing season, to allow for correlation of any positive or negative relationship between growth/survival and rainfall for the first growing season.

Pre-emergent Herbicide Application of Oust® XP

On March 7, 2019, Oust® XP was applied over-the-top of all planted seedlings prior to bud break at a rate of 140 grams of Oust® XP per hectare. Herbicide was applied using an 11.4-liter (l) Solo diaphragm-pump backpack sprayer equipped with a TK 2.5 flood jet nozzle. The sprayed band was approximately 1.5 meters wide centered over seedlings.

In March 2020, prior to bud break of oak seedlings, Oust® XP was applied in the same manner as the initial spray application. The rate of 140 grams of Oust® XP per hectare was used. The same backpack-nozzle combination was also used for this second application.

Ground Cover Evaluation

To better understand the effectiveness of Oust® XP in controlling herbaceous competition on each site, ocular evaluations were conducted monthly for the first growing season at the same time as survival counts. Evaluations estimated percent ground coverage of grasses or forbs. Spray bands were the treatment areas, and untreated areas between rows were considered to be control plots. This evaluation was used to better understand how competing vegetation, or the lack thereof, can affect growth and survival of seedlings.

Survival Inventory

Monthly survival counts began in April 2019 and continued until October 2019 for all seedlings on both sites. The purpose of survival counts during the first growing season was to allow a better understanding of mortality causes. Planting shock, physical damage, and moisture stress are common causes of mortality during the first growing season. Survival was recorded again in late September 2020. Survival was recorded on the same day for both sites to reduce bias. If a seedling appeared dead, bark was scratched at the seedling base. If the cambium was green, the seedling was assumed alive; and if the cambium was brown or black, the seedling was considered dead. Any herbivory, dieback, or other factor that could negatively impact seedling growth was recorded. It was recorded if a seedling marked as dead resprouted from the root collar. This seedling was considered alive again.

Tree Measurements

On March 9, 2019, initial measurements of height and groundline diameter (GLD) were recorded for all seedlings. First year measurements of height and GLD were recorded in early October 2019. Second year measurements of height and GLD were recorded in late September 2020. Heights were measured using a meter stick and recorded to the nearest whole centimeter. Heights were measured from the ground to the dominant apical bud. In the case of multiple stems on a seedling, the dominant stem was measured. GLD was measured and recorded to the nearest tenth of a millimeter (mm) using digital calipers at a point as near the soil surface as possible. Assuming proper planting, in which the root collar should have been placed slightly under the soil, this measurement would take place directly above the root collar. In the case of a

seedling which forks below the groundline, GLD corresponding to the dominant stem was measured.

Experimental Design and Analysis

Data were analyzed using Statistical Analysis System (SAS) software version 9.4® with statistical models appropriate for randomized complete block design (SAS 2013).

PROC GLM was used to perform analysis of variance (ANOVA) to determine if treatments or interactions between treatments caused differences in survival, GLD growth, or height growth. This analysis tested for differences between species, planting stocks, sites, and any interactions among those factors. To determine significant differences within groups, a multiple comparison procedure (MCP) was used, where appropriate, to determine significance using the LSMEANS statement with the Tukey-Kramer method. PROC GLM, LSMEANS, and Tukey-Kramer comparisons were utilized because sample populations were not equal due to mortality and because it accounts for all pairwise comparisons (Salkind 2007). Any seedling that died back to the root collar and resprouted later on was not included in analysis of height and GLD. Due to a lack of normality, height and groundline diameter data measurements were transformed using a log transformation, while survival data was transformed using an arcsine square root transformation. Untransformed means were reported in the Results section.

Differences were considered significant at the $\alpha=0.05$ level. Height, groundline diameter, and survival numbers were rounded to the nearest one-tenth of their respective unit of measurement.

Hypotheses tested were as follows:

- I. Nuttall oak seedling survival, height growth, and groundline diameter growth will be equal to that of swamp chestnut oak seedlings.
 - i. H_0 : Nuttall oak survival = swamp chestnut oak survival
 H_1 : Nuttall oak survival \neq swamp chestnut oak survival
 - ii. H_0 : Nuttall oak height growth = swamp chestnut oak height growth
 H_1 : Nuttall oak height growth \neq swamp chestnut oak height growth
 - iii. H_0 : Nuttall oak GLD growth = swamp chestnut oak GLD growth
 H_1 : Nuttall oak GLD growth \neq swamp chestnut oak GLD growth

- II. Bareroot seedling survival, height growth, and groundline diameter growth will be equal to that of containerized seedlings.
 - i. H_0 : Bareroot survival = containerized survival
 H_1 : Bareroot survival \neq containerized survival
 - ii. H_0 : Bareroot height growth = containerized height growth
 H_1 : Bareroot height growth \neq containerized height growth
 - iii. H_0 : Bareroot GLD growth = containerized GLD growth
 H_1 : Bareroot GLD growth \neq containerized GLD growth

CHAPTER IV

RESULTS

Ground Coverage

Carney Site

Broadleaf Coverage

Very little broadleaf competition was present on the Carney site prior to planting due to routine bush hogging. Bull thistle (*Cirsium vulgare*) and white clover (*Trifolium repens*) were the only broadleaf species visibly present and each covered approximately one percent of the study area. As the first growing season progressed, bull nettle (*Cnidoscolus texanus*), American burnweed (*Erechtites hieracifolius*), dog fennel (*Eupatorium capillifolium*), and goldenrod (*Solidago spp.*) began to colonize treated and untreated areas of the site.

Broadleaf competition within treated and untreated areas remained low in April and May. By June, treated areas produced total broadleaf coverage of five percent, while untreated areas total broadleaf coverage was 10%. July brought higher levels of total broadleaf coverage for both treated (10%) and untreated (15%) areas of the Carney site (Table 4.1).

Effects of the Oust® XP treatment began to dissipate by August, as treated areas total broadleaf coverage climbed to 20%. Untreated areas were 25% covered by broadleaf species. By September, broadleaf species covered 35% of treated areas and 55% of untreated areas (Table 4.1).

Table 4.1 Average percent coverage of broadleaf competition found in treated and untreated areas on both study sites during the first growing season (average of all plots).

Site	Competition/Treatment	Mar.	Apr.	May	June	July	Aug.	Sept.
Carney	Broadleaf Treated	2	2	2	5	10	25	35
Carney	Broadleaf Untreated	2	2	2	10	15	25	55
Malone	Broadleaf Treated	1	2	5	25	30	33	35
Malone	Broadleaf Untreated	1	40	60	65	65	65	65

Grass coverage

Dominant cover type for the Carney site prior to planting was grasses. Species observed include bahiagrass (*Paspalum notatum*), perennial ryegrass (*Lolium perenne*), Bermudagrass (*Cynodon dactylon*), broomsedge (*Andropogon virginicus*), Dichanthelium grasses (*Dichanthelium spp.*), and foxtail grasses (*Setaria spp.*). At the time of planting, total ground coverage by grasses was estimated to be 90%, though most were dormant at the time. Grass height and biomass were reduced prior to planting by bush hogging (Table 4.2).

Oust XP treatment substantially reduced grass coverage in treatment areas. By April, only four percent of the ground was covered by grasses in treated areas while untreated areas still had 90% coverage. Grass coverage of treated areas in May was estimated to be five percent, while untreated area coverage was estimated at 99% (Table 4.2).

By June, grasses began to recolonize treated areas and 50% coverage of grasses was observed, while untreated areas reached 105% coverage. It should be noted that coverage of over 100% is possible due to a layering effect of various grass species as they grow to different heights and compete amongst themselves. Grass coverage of treated areas increased to 75% in July, 90% in August, and 98% in September. Untreated areas remained at 105% grass coverage through September (Table 4.2).

A wet region on the southwest corner of the Carney study area remained moist throughout the growing season, and as a result rushes (*Juncus spp.*) colonized the area. Oust® XP does not control rush species, so coverage in this area was consistent between treated and untreated areas. Coverage by rushes within this area was estimated to be around 25% at its peak, but it is not believed to have had any detrimental effects on oak seedlings.

Table 4.2 Average percent coverage of grass competition found in treated and untreated areas on both study sites during the first growing season (average of all plots)*.

Site	Competition/Treatment	Mar.	Apr.	May	June	July	Aug.	Sept.
Carney	Grasses Treated	90	4	5	50	75	90	98
Carney	Grasses Untreated	90	90	99	105	105	105	105
Malone	Grasses Treated	50	4	5	15	25	40	50
Malone	Grasses Untreated	50	75	95	95	95	95	95

*Coverage can exceed 100% due to a layering effect of competition.

Woody coverage

There was no woody competition present within the study area of the Carney site at the time of planting, though it was noted that several hundred stems of Chinese tallow (*Triadica sebifera*) and black willow (*Salix nigra*) were present around the periphery of the study area. Oust® XP does not control most woody species.

Woody competition first became visible in July as Chinese tallow and black willow began to invade the western half of the study area. A few stems of Southern catalpa (*Catalpa bignonioides*) began to appear as well, all of which were likely sprouts of larger stems removed by bush hogging site preparation. Total woody coverage was estimated at four percent in July for both treated and untreated areas. By August, Chinese tallow coverage increased in the western half of the study area and accounted for eight percent coverage across the site, causing total

woody coverage to rise to 10%. It remained at 10% through the end of the growing season (Table 4.3).

Table 4.3 Average percent coverage of woody competition found in treated and untreated areas on both study sites during the first growing season (average of all plots).

Site	Competition/Treatment	Mar.	Apr.	May	June	July	Aug.	Sept.
Carney	Woody Treated	0	0	0	0	4	10	10
Carney	Woody Untreated	0	0	0	0	4	10	10
Malone	Woody Treated	0	1	3	5	12	25	40
Malone	Woody Untreated	0	1	3	5	12	25	40

Malone site

Broadleaf coverage

Broadleaf coverage on the Malone site was low prior to planting due to bush hogging. However, it was observed that many broadleaf species had been present through the residual biomass left behind from the bush hog. As the first growing season progressed, many species were observed including bull nettle, Brazilian verbena (*Verbena bonariensis*), goldenrod, flat-topped goldenrod (*Euthamia tenuifolia*), American burnweed, dog fennel, common ragweed (*Ambrosia artemisiifolia*), giant ragweed (*Ambrosia trifida*), narrowleaf sunflower (*Helianthus angustifolius*), late boneset (*Eupatorium serotinum*), and white clover (*Trifolium repens*).

Oust® XP greatly reduced broadleaf coverage within treated areas to two percent while untreated areas had 40% ground coverage as early as April. By May, broadleaf coverage within treated areas climbed to five percent while untreated areas climbed to 60% coverage. Effects of Oust® XP begin to decline in June, as broadleaf coverage in treated areas grew to 25%, though coverage was substantially lower than untreated areas (65%). Broadleaf coverage in treated areas

increased to 30% in July, 33% in August, and 35% in September. Broadleaf coverage in untreated areas remained at 65% for the remainder of the first growing season (Table 4.1).

Grass coverage

Grasses were the most abundant competitor on the Malone site prior to planting, as the area had been maintained as a wildlife food plot through disking and planting for several years. Primary grass species observed on the Malone site include foxtail grasses, Dichanthium grasses, wildrye (*Elymus canadensis*), greasygrass (*Tridens strictus*), silver plumegrass (*Saccharum spp.*), bahiagrass, and perennial ryegrass. A small patch of cogongrass (*Imperata cylindrica*) was discovered in May and grew through the end of the first growing season, though it only covered approximately three percent of the study area at the end of the first growing season. At the time of planting, grass coverage was estimated at 50% across the Malone site but height and total biomass had been greatly reduced through bush hogging.

Oust® XP controlled grass competition within treated areas very well, as only four percent coverage was observed in April. Untreated areas contained 75% coverage of grasses in April. Treated area grass coverage was estimated to be five percent for May while untreated area coverage was estimated at 95%. Grass coverage within treated areas increased to 15% for June, 25% for July, 40% for August, and 50% for September. Untreated area grass coverage remained at 95% through the end of the growing season (Table 4.2).

Woody coverage

Woody coverage was not evident in the research area of the Malone site at the time of planting due to bush hogging, but severed woody stems were visible across the site. Resprouts from cut stems developed through the summer and grew to be a large competitor by the end of the growing season. Species observed include common persimmon (*Diospyros virginiana*) and American beautyberry (*Callicarpa americana*). Common persimmon accounted for the majority of woody competition across the site. As many as 15 stems resprouted from each individual stump left behind by bush hogging. These stems produced substantial crowns and covered a large portion of ground. The stems also grew tall in some cases, reaching heights of nearly four meters in the first growing season. It is expected that these common persimmon stems will compete with oak seedlings in this study for several years.

Woody coverage was consistent between treated and untreated areas of the study site, as Oust® XP does not control these species. Common persimmon began to resprout from stumps beginning in April, but only accounted for one percent coverage of the site at that time. American beautyberry began to sprout in May and total woody coverage was estimated to be three percent across the site. Woody coverage increased to five percent in June, 12% in July, 25% in August, and 40% in September (Table 4.3).

Vine coverage

Vine coverage was nonexistent at the time of planting. Purple passionflower (*Passiflora incarnata*) was the primary competitor, with blackberry (*Rubus spp.*) making up a lesser component of vine competition by the end of the first growing season. Purple passionflower

grew up the oak seedlings' stems. The weight of the vine caused oak seedlings to bend over and then allocate resources to a branch that developed apical dominance. This splitting of resources between multiple dominant stems over the course of the first growing season may have reduced height growth of these individuals, but it is not believed that this will impact overall results over the course of this study.

Vine coverage was not observed until July, when both purple passionflower and blackberry appeared. Vine coverage in July was estimated to be three percent and increased to eight percent in August and 15% in September. Purple passionflower accounted for 93.3% of all vine coverage at the end of the first growing season (Table 4.4).

Table 4.4 Average percent coverage of vine competition found in treated and untreated areas on both study sites during the first growing season (average of all plots).

Site	Competition/Treatment	Mar.	Apr.	May	June	July	Aug.	Sept.
Carney*	Vines Treated	0	0	0	0	0	0	0
Carney*	Vines Untreated	0	0	0	0	0	0	0
Malone	Vines Treated	0	0	0	0	3	8	15
Malone	Vines Untreated	0	0	0	0	3	8	15

*No vine competition observed on the Carney site during the first growing season.

Survival

Analysis of Variance

The effects of planting stock, site, species/planting stock, and species/site were statistically significant for survival after the first (2019) and second (2020) growing seasons (Table 4.5).

Table 4.5 ANOVA results for survival by year and overall. Bolded values are statistically significant.

Source	DF	Growing Season			
		2019		2020	
		F	P>F	F	P>F
(A) Species	1	0.03	0.8556	0.80	0.3707
(B) Stock	1	11.97	0.0006	9.07	0.0026
(C) Site	1	50.41	<.0001	67.59	<.0001
A*B	1	16.04	<.0001	17.23	<.0001
B*C	1	0.13	0.7158	0.80	0.3707
A*C	1	8.49	0.0036	9.07	0.0026
A*B*C	1	1.62	0.2026	1.49	0.2222

Monthly survival and precipitation during first growing season

Monthly survival evaluations were conducted during the first growing season to determine impact of transplant shock on seedlings. Monthly precipitation was recorded using a rain gauge on each site. Precipitation data paired with monthly survival records allowed for rainfall’s impact on survival to be quantified.

Monthly precipitation by site during first growing season

Precipitation during the 2019 growing season was somewhat similar across both sites (Tables 4.6 and 4.7) and comparable to monthly long-term averages in each site’s area (U.S. Climate data 2019). During the months of April and May, both sites received rainfall totals well above long-term averages for the area. During June, both sites received rainfall totals slightly below their respective long-term average. Rainfall was again above average for the Malone site during July and August, while the Carney site received well below average rainfall during July and August. Both sites received below average rainfall during September. Below average rainfall

for the Carney site during the months of June, July, and August does correspond to decreases in survival, but survival on both sites was still considered very good to excellent at the end of the first growing season.

Table 4.6 Average monthly and total rainfall for the 2019 growing season on the Carney site compared to average monthly rainfall for Columbia, MS (1981-2010), in centimeters.

	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Total
Malone	3.3	25.1	18.5	8.9	16.4	16.8	4.1	93.1
1981-2010 Average*	13.6	12.6	11.3	12.3	14.4	14.5	11.4	90.1

*Source: U.S. Climate Data 1. (2019)

Table 4.7 Average monthly and total rainfall for the 2019 growing season on the Malone site compared to average monthly rainfall for Hattiesburg, MS (1981-2010), in centimeters.

	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Total
Carney	1.0	22.9	18.2	13.4	8.1	6.8	2.3	72.7
1981-2010 Average*	14.4	13.3	12.5	13.9	13.5	12.2	9.7	89.5

*Source: U.S. Climate Data 2. (2019)

Soil Nutrient and Texture Analysis

The Carney site had higher concentrations of four of the seven elements tested (P, K, S, Zn) (Table 4.8). Both sites had a soil pH considered acidic and within the acceptable range (4.5-6.5) for these species (Table 4.9). Organic matter content within the soil was fairly consistent between sites (Table 4.9).

The Carney site was classified as a sandy loam due. The Malone site was classified as a silt loam. The higher sand content may have contributed to decreased survival at the Carney site

when combined with less precipitation. Clay content was similar between sites (Table 4.9). The Carney site displayed a higher cation exchange capacity than the Malone site (Table 4.9).

Table 4.8 Soil texture, cation exchange capacity, organic matter content, and pH for the Carney and Malone study sites.

Site	% Clay	% Silt	% Sand	Texture	CEC	% OM	pH
Carney	4	28	68	Sandy Loam	6.7	2.5	5.2
Malone	3	64	33	Silt Loam	6.1	2.4	5.5

Table 4.9 Extractable nutrient levels of the soils found on the Carney and Malone study sites (kg/ha).

Site	P	K	Ca	Mg	S	Zn	Na
Carney	84	104	475	76	403	20	43
Malone	82	67	956	90	388	3	55

Monthly survival during the first growing season

Survival was very good on both sites, between both species and both planting stocks for the first growing season (Table 4.10). Overall survival remained above 99% until June, when rainfall totals dipped below the long-term average for both sites. From June through the end of the growing season, the Carney site experienced a combination of drought and rabbit herbivory. This resulted in lower survival rates in treatments on the Carney site compared to treatments on the Malone site through the first growing season.

A three percent decrease in overall survival was attributed to rabbits on the Carney site during the first growing season. The majority of this mortality was in bareroot Nuttall oak seedlings, in which rabbits caused 81.8% of the mortality recorded in the first growing season. Rabbits caused 25% of the mortality in bareroot swamp chestnut oak and 22.2% of the mortality

in containerized Nuttall oak. Containerized swamp chestnut oak had only one individual killed by rabbits (0.03% of the mortality recorded for those seedlings).

Table 4.10 Monthly survival per treatment by site during the first growing season, shown as a percent.

Site	Treatment	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.
Carney	Bareroot Nuttall oak	99.7	99.7	99.7	90.0	90.0	90.0	90.0	89.0
	Bareroot swamp chestnut oak	100	100	100	98.7	98.0	97.3	97.3	96.3
	Cont. Nuttall oak	99.7	99.7	99.3	95.7	95.7	93.0	91.7	91.0
	Cont. swamp chestnut oak	100	100	100	96.0	92.0	91.0	90.0	88.7
Malone	Bareroot Nuttall oak	100	100	100	100	100	100	100	99.7
	Bareroot swamp chestnut oak	100	100	100	99.7	99.7	99.3	99.3	99.3
	Cont. Nuttall oak	99.7	99.7	99.7	99.3	99.0	98.7	98.7	98.7
	Cont. swamp chestnut oak	100	100	99.7	95.7	95.3	93.7	93.3	93.3

Survival variation between species

Analysis of variance failed to show significant effect of species on survival during the first ($F= 0.03$, $p= 0.856$) or second growing season ($F= 0.80$, $p= 0.371$) (Table 4.5).

At the end of the first growing season, both species displayed excellent survival rates, with no significant difference observed between them. When comparing species across both sites and planting stocks, Nuttall oak survival was slightly higher, at 94.6%, compared to swamp chestnut oak at 94.4% during the first growing season. The slight difference in survival between species continued during the second growing season with Nuttall oak having 93.4% survival and swamp chestnut oak having 92.5% survival overall. This difference remained statistically insignificant (Table 4.11).

Table 4.11 Survival by species at the end of each growing season, shown as a percent (both sites and both planting stocks).

Species	2019	2020
Nuttall oak	94.6a*	93.4a
Swamp chestnut oak	94.4a	92.5a

*Values in column followed by the same letter do not differ at $\alpha=0.05$.

Survival variation among planting stocks

Analysis of variance revealed an effect of planting stock on survival during the first ($F=11.97$, $p=0.001$) and second growing season ($F=9.07$, $p=0.003$) (Table 4.5).

At the end of the first growing season, bareroot seedlings displayed a significantly higher survival rate (96.1%) than containerized seedlings (92.9%) across both sites and species. During the second growing season, bareroot survival (94.5%) remained higher than containerized survival (91.4%). It is worth noting that while this difference between planting stocks may be statistically significant, it has little biological or management significance (Table 4.12).

Table 4.12 Survival by planting stock at the end of each growing season, shown as a percent (both sites and both species).

Planting Stock	2019	2020
Bareroot	96.1a*	94.5a
Conventional containerized	92.9b	91.4b

*Values in column followed by the same letter do not differ at $\alpha=0.05$.

Survival variation between sites

Analysis of variance revealed an effect of site on survival during the first ($F=50.41$, $p<0.001$) and second growing season ($F=67.59$, $p<0.001$) (Table 4.5).

Survival was significantly higher at the Malone site (97.8%) than the Carney site (91.3%) through the first growing season, though both were still considered very good to excellent for stand establishment purposes. The difference between sites continued during the second growing season as survival at the Malone site was 97.2% and survival at the Carney site was 88.8% (Table 4.13).

Table 4.13 Survival by site at the end of each growing season, shown as a percent (both species and both planting stocks).

Site	2019	2020
Carney	91.3b*	88.8b
Malone	97.8a	97.2a

*Values in column followed by the same letter do not differ at $\alpha=0.05$.

Survival variation by planting stock and species interactions

Analysis of variance revealed a significant interaction between planting stock and species on survival during the first ($F= 16.04, p<0.001$) and second growing season ($F= 17.23, p< 0.001$) (Table 4.5). MCP analysis was then utilized to determine which interactions were significant.

Bareroot swamp chestnut oak had the highest survival through the first growing season at 97.8% (Table 4.14). Containerized Nuttall oak had the next highest first year survival (94.8%) but was not significantly different from bareroot swamp chestnut oak seedlings. Bareroot Nuttall oak seedlings displayed the third highest survival rate through the first growing season at 94.3%, which was significantly less than bareroot swamp chestnut oak but not containerized Nuttall oak. Containerized swamp chestnut oak had the lowest survival rate at 91.0% which was significantly lower than all other treatments.

During the second growing season, the ranked order of treatment survival rates, as well as significant differences between treatments, remained the same as the first growing season, with all values being slightly lower. Bareroot swamp chestnut oak displayed the highest survival (96.2%), followed by Containerized Nuttall oak (94.0%), Bareroot Nuttall oak (92.8%), and containerized swamp chestnut oak (88.8%) (Table 4.14).

Table 4.14 Survival by planting stock and species at the end of each growing season, shown as a percent (both sites).

Species/Planting Stock	2019	2020
Bareroot Nuttall oak	94.3b*	92.8b
Conventional containerized Nuttall oak	94.8ab	94.0ab
Bareroot swamp chestnut oak	97.8a	96.2a
Conventional containerized swamp chestnut oak	91.0c	88.8c

*Values in column followed by the same letter do not differ at $\alpha=0.05$.

Survival variation by planting stock and site interaction

Analysis of variance failed to show a significant interaction between planting stock and sites during the first ($F= 0.13$, $p= 0.716$) or second growing season ($F= 0.80$, $p= 0.371$) (Table 4.5).

Planting stocks on the Malone site exhibited the two highest survival rates (bareroot= 99.5%, containerized= 96.0%) for the first growing season (Table 4.15). These two survival rates were significantly different from one another. The Carney site had the two lowest survival rates (bareroot= 92.7%, containerized= 89.8%) which were both significantly lower than either planting stock on the Malone site, but not significantly different from one another. This is further evidence of the influence of growing conditions on the Carney site.

This trend continued through the second growing season as both planting stocks on the Malone site outperformed either planting stock on the Carney site. Bareroot seedlings on the Malone site remained at 99.2% survival while containerized seedling fell to 95.2%. The difference between planting stock survival on the Malone site remained significant during the second growing season. Bareroot and containerized seedling survival on the Carney site were not significantly different from one another (bareroot= 89.8%, containerized= 87.7%) during the second growing season but were significantly lower than either planting stock on the Malone site (Table 4.15).

Table 4.15 Survival by planting stock and site at the end of each growing season, shown as a percent (both species).

Planting stock/Site	2019	2020
Bareroot Carney site	92.7c*	89.8c
Bareroot Malone site	99.5a	99.2a
Conventional containerized Carney site	89.8c	87.7c
Conventional containerized Malone site	96.0b	95.2b

*Values in column followed by the same letter do not differ at $\alpha=0.05$.

Survival variation by species and site interaction

Analysis of variance revealed a significant interaction between species and sites in regard to survival during the first ($F= 8.49$, $p= 0.004$) and second growing season ($F= 9.07$, $p= 0.003$) (Table 4.5).

Nuttall oak (99.2%) and swamp chestnut oak (96.3%) on the Malone site had the highest two survival rates among species/site combinations during the first growing season (Table 4.16). The two were not significantly different from one another but were significantly higher than either species/site combination on the Carney site. Swamp chestnut oak on the Carney site

survived at a rate of 92.5% through the first growing season, while Nuttall oak survived at 90.0%. These two species/site interactions were not significantly different from one another.

During the second growing season, Nuttall oak on the Malone site remained at 99.2% survival which was significantly higher than that of swamp chestnut oak on the Malone site (95.2%). Swamp chestnut oak on the Carney site (89.8%) and Nuttall oak on the Carney site (87.7%) were not significantly different from one another but were significantly lower than either species on the Malone site (Table 4.16).

Table 4.16 Survival by species and site at the end of each growing season, shown as a percent (all planting stocks).

Species/Site	2019	2020
Nuttall oak Carney site	90.0b*	87.7c
Nuttall oak Malone site	99.2a	99.2a
Swamp chestnut oak Carney site	92.5b	89.8c
Swamp chestnut oak Malone site	96.3a	95.2b

*Values in column followed by the same letter do not differ at $\alpha=0.05$.

Survival variation by treatment and site interaction

Analysis of variance failed to show a significant interaction between species, planting stocks, and sites during the first ($F= 1.62$, $p= 0.203$) or second growing season ($F= 1.49$, $p= 0.222$) (Table 4.5).

Bareroot Nuttall oak (99.7%), bareroot swamp chestnut oak (99.3%), and containerized Nuttall oak (98.7%) on the Malone site had the highest survival at the end of the first growing season (Table 4.17). Their survival was not significantly different from survival of bareroot swamp chestnut oak on the Carney site (96.3%). However, their survival was significantly higher than containerized swamp chestnut oak on the Malone site (93.3%) and containerized Nuttall oak

on the Carney site (91.0%). As well as containerized swamp chestnut oak on the Carney site (89.7% percent), and bareroot Nuttall oak on the Carney site (89.0%).

Bareroot Nuttall oak, bareroot swamp chestnut oak, and containerized Nuttall oak on the Malone site remained the highest with survival (99.7%, 98.7%, and 98.7%, respectively) through the second growing season. Their survival was not significantly different from that of bareroot swamp chestnut oak on the Carney site (93.7%) but was significantly higher than containerized swamp chestnut oak on the Malone site (91.7%) and containerized Nuttall oak on the Carney site (89.3%). Bareroot Nuttall oak on the Carney site (86.0%) and containerized swamp chestnut oak on the Carney site (86.0%) had the lowest survival rates but were not significantly different from one another (Table 4.17).

Table 4.17 Survival by treatment and site at the end of each growing season, shown as a percent.

Species	Planting stock/Site	2019	2020
Nuttall oak	Bareroot Carney site	89.0d*	86.0c
	Bareroot Malone site	99.7a	99.7a
	Conventional containerized Carney site	91.0cd	89.3bc
	Conventional containerized Malone site	98.7ab	98.7a
Swamp chestnut oak	Bareroot Carney site	96.3abc	93.7ab
	Bareroot Malone site	99.3a	98.7a
	Conventional containerized Carney site	89.7d	86.0c
	Conventional containerized Malone site	93.3bcd	91.7bc

*Values in column followed by the same letter do not differ at $\alpha=0.05$.

Groundline Diameter Growth

Analysis of variance

The effects of species, planting stock, site, planting stock/site, species/site, and species/planting stock/site were statistically significant for groundline diameter growth after the first (2019) growing season and overall. Effects of species, planting stock, species/site, and species/planting stock/site were statistically significant for groundline diameter growth after the second (2020) growing seasons (Table 4.18).

Table 4.18 ANOVA results for average groundline diameter growth by year and overall. Bolded values are statistically significant.

Source	DF	Growing Season					
		2019		2020		Overall	
		F	P>F	F	P>F	F	P>F
(A) Species	1	492.12	<.0001	522.87	<.0001	835.34	<.0001
(B) Stock	1	30.08	<.0001	101.94	<.0001	22.08	<.0001
(C) Site	1	442.60	<.0001	0.74	0.3890	132.03	<.0001
A*B	1	0.36	0.5500	0.37	0.5413	0.06	0.8117
B*C	1	27.39	<.0001	3.27	0.0708	17.44	<.0001
A*C	1	60.29	<.0001	5.89	0.0153	32.67	<.0001
A*B*C	1	49.95	<.0001	13.48	0.0002	44.27	<.0001

GLD growth variation between species

ANOVA revealed an effect of species on groundline diameter growth during the first growing season (F= 492.12, p< 0.001), second growing season (F= 522.87, p< 0.001), and overall (F= 835.34, p< 0.001) (Table 4.18). Groundline diameter growth was significantly higher for Nuttall oak (5.2 mm) during the first growing season when compared to swamp chestnut oak (2.7 mm) (Table 4.19). This trend continued during the second growing season as Nuttall oak produced 7.8 mm of GLD growth while swamp chestnut oak produced only 3.9 mm of growth.

Combining the two growing season's GLD growth, Nuttall oak nearly doubled the growth of swamp chestnut oak (13.0 mm compared to 6.6 mm) (Table 4.19).

Table 4.19 Average groundline diameter growth by species for each growing season and overall, measured in millimeters (both sites and both planting stocks).

Species	2019	2020	Overall
Nuttall oak	5.2a*	7.8a	13.0a
Swamp chestnut oak	2.7b	3.9b	6.6b

*Values in column followed by the same letter do not differ at $\alpha=0.05$.

GLD growth variation between planting stocks

ANOVA revealed an effect of planting stock on groundline diameter growth during the first growing season ($F= 30.08$, $p< 0.001$), second growing season ($F= 101.94$, $p< 0.001$), and overall ($F= 22.08$, $p< 0.001$) (Table 4.18).

Containerized seedlings (4.3 mm) displayed significantly more groundline diameter growth when compared to bareroot seedlings (3.6 mm) during the first growing season (Table 4.20). This trend reversed during the second growing season as bareroot seedlings (6.7 mm) outperformed containerized seedlings (5.0 mm) in regard to GLD growth. When considering groundline diameter growth over both growing seasons combined, bareroot seedlings grew 10.3 mm while containerized grew only 9.3 mm (Table 4.20).

Table 4.20 Average groundline diameter growth by planting stock for each growing season and overall, measured in millimeters (both sites and both species).

Planting stock	2019	2020	Overall
Bareroot	3.6b*	6.7a	10.3a
Conventional containerized	4.3a	5.0b	9.3b

*Values in column followed by the same letter do not differ at $\alpha=0.05$.

GLD growth variation between sites

ANOVA revealed an effect of site on groundline diameter growth during the first growing season ($F= 442.60$, $p< 0.001$) and overall ($F=132.03$, $p< 0.001$). There was no significant effect of site on groundline diameter growth detected during the second growing season ($F= 0.74$, $p= 0.389$) (Table 4.18). During the first growing season, the Malone site (5.1 mm) displayed superior GLD growth when compared to the Carney site (2.7 mm) (Table 4.21). GLD was not significantly different between sites for the second growing season as the Malone site produced 5.9 mm of growth and the Carney site produced 5.8 mm. When adding growth for both growing seasons, the Malone site (11.1 mm) outperformed the Carney site (8.5 mm) in regard to GLD growth overall, with the difference between the two coming primarily from the first growing season.

Table 4.21 Average groundline diameter growth by site for each growing season and overall, measured in millimeters (both planting stocks and both species).

Site	2019	2020	Overall
Carney	2.7b*	5.8a	8.5b
Malone	5.1a	5.9a	11.1a

*Values in column followed by the same letter do not differ at $\alpha=0.05$.

GLD growth variation by planting stock and species interaction

ANOVA failed to show a significant interaction between planting stock and species in groundline diameter growth during the first growing season ($F= 0.36$, $p= 0.550$), second growing season ($F= 0.37$, $p= 0.541$), or overall ($F= 0.06$, $p= 0.812$) (Table 4.18). Containerized Nuttall oak seedlings displayed the largest GLD growth (5.5 mm) during the first growing season and were significantly higher than all other combinations (Table 4.22). Bareroot Nuttall oak (4.8

mm), containerized swamp chestnut oak (3.0 mm), and bareroot swamp chestnut oak (2.4 mm) were all significantly different from one another.

During the second growing season, bareroot Nuttall oak produced the most GLD growth (8.6mm) which was significantly greater than all other treatments. Containerized Nuttall oak seedlings produced 7.0 mm of growth while bareroot swamp chestnut oak produced 4.8 mm and containerized swamp chestnut oak produced 3.0 mm (Table 4.22). All treatments were significantly different from one another for the second growing season.

When looking at data combined for both growing seasons, all treatments remained significantly different from one another with bareroot Nuttall oak (13.4 mm) outperforming containerized Nuttall oak (12.6 mm), bareroot swamp chestnut oak (7.2 mm), and containerized swamp chestnut oak (6.1 mm) (Table 4.22).

Table 4.22 Average groundline diameter growth by species and planting stock for each growing season and overall, measured in millimeters (both sites).

Species/Planting stock	2019	2020	Overall
Bareroot Nuttall oak	4.8b*	8.6a	13.4a
Conventional containerized Nuttall oak	5.5a	7.0b	12.6b
Bareroot swamp chestnut oak	2.4d	4.8c	7.2c
Conventional containerized swamp chestnut oak	3.0c	3.0d	6.1d

*Values in column followed by the same letter do not differ at $\alpha=0.05$.

GLD growth variation by planting stock and site interaction

ANOVA revealed a significant interaction between planting stock and site in groundline diameter growth during the first growing season ($F= 27.39, p< 0.001$) and overall ($F= 17.44, p< 0.001$), but not during the second growing season ($F= 3.27, p= 0.071$) (Table 4.18). MCP analysis was then utilized to determine which interactions were significant.

Both planting stocks on the Malone site displayed significantly more GLD growth (bareroot= 5.1 mm, containerized= 5.2 mm) than either planting stock on the Carney site (bareroot=2.1 mm, containerized= 3.4 mm) during the first growing season (Table 4.23).

Conventional containerized seedlings on the Carney site displayed significantly greater GLD growth when compared to bareroot seedlings on the same site during the first growing season.

During the second growing season, the influence of planting stock was greater than that of site. GLD growth of bareroot seedlings on both the Malone (6.9 mm) and Carney (6.5 mm) sites was not significantly different but was significantly greater than containerized seedlings on either site. Containerized seedlings on the Malone site outperformed containerized seedlings on the Carney site (5.1 mm and 4.9 mm, respectively), though they were not significantly different from one another (Table 4.23).

When combining the two growing seasons cumulative data, bareroot seedling growth on the Malone site (12.0 mm) was significantly higher than all other combinations. Containerized seedlings on the Malone site produced 10.1 mm of groundline diameter growth. Bareroot seedlings and containerized seedlings both grew 8.5 mm on the Carney site and were significantly less than either planting stock on the Malone site (Table 4.23).

Table 4.23 Average groundline diameter growth by planting stock and site for each growing season and overall, measured in millimeters (both species).

Planting stock/Site	2019	2020	Overall
Bareroot Carney site	2.1c*	6.5a	8.5c
Bareroot Malone site	5.1a	6.9a	12.0a
Conventional containerized Carney site	3.4b	5.1b	8.5c
Conventional containerized Malone site	5.2a	4.9b	10.1b

*Values in column followed by the same letter do not differ at $\alpha=0.05$.

GLD growth variation by species and site interaction

ANOVA revealed a significant interaction between species and site in groundline diameter growth during the first growing season ($F= 60.29$, $p< 0.001$), second growing season ($F= 5.89$, $p= 0.015$), and overall ($F= 32.67$, $p< 0.001$). (Table 4.18). MCP analysis was then utilized to determine which interactions were significant.

Nuttall oak on the Malone site displayed significantly more GLD growth (6.8 mm) during the first growing season than all other species/site combinations (Table 4.24). No significant difference was noted between GLD growth of Nuttall oak on the Carney site and swamp chestnut oak on the Malone site (both= 3.5 mm), while swamp chestnut oak on the Carney site displayed the lowest GLD growth of all combinations (1.9 mm).

Nuttall oak on the Malone site (8.1 mm) outperformed all other species/site combinations during the second growing season as well but analysis did not indicate that they were significantly different from Nuttall oak on the Carney site (7.5 mm) in regard to GLD growth. However, both were significantly higher than either swamp chestnut oak on the Carney site (4.0 mm) or swamp chestnut oak on the Malone site (3.8 mm), which did not test significantly different from one another (Table 4.24).

When combining both growing seasons data, GLD growth of Nuttall oak on the Malone site was significantly higher than all other combinations and produced 14.9 mm of growth overall. GLD of Nuttall oak on the Carney site was the next highest with 11.1 mm, followed by swamp chestnut oak on the Malone site (7.3 mm) and swamp chestnut oak on the Carney site (6.0 mm). All combinations were significantly different from one another in overall GLD growth (Table 4.24).

Table 4.24 Average groundline diameter growth by species and site for each growing season and overall, measured in millimeters (both planting stocks).

Species/Site	2019	2020	Overall
Nuttall oak Carney site	3.5b*	7.5a	11.1b
Nuttall oak Malone site	6.8a	8.1a	14.9a
Swamp chestnut oak Carney site	1.9c	4.0b	6.0d
Swamp chestnut oak Malone site	3.5b	3.8b	7.3c

*Values in column followed by the same letter do not differ at $\alpha=0.05$.

GLD growth variation by treatment and site interaction

ANOVA revealed a significant interaction among species, planting stock, and site for GLD growth during the first growing season ($F= 49.95$, $p< 0.001$), second growing season ($F= 13.48$, $p<.001$), and overall ($F= 44.27$, $p< 0.001$) (Table 4.18). MCP analysis was then utilized to determine which interactions were significant.

Both planting stocks of swamp chestnut oak seedlings on the Carney site experienced the least GLD growth (bareroot= 1.7mm, containerized= 2.2mm) (Table 4.25). Bareroot Nuttall oak on the Carney site performed similarly (2.5 mm) but was significantly different from bareroot swamp chestnut oak of the same site. The Carney site had the three treatments with the least GLD growth, with only containerized Nuttall oak (4.5 mm) of the Carney site statistically similar to treatments on the Malone site during the first growing season.

The Malone site produced three of the top four treatments in GLD growth during the first growing season. Bareroot Nuttall oak displayed the most first-year GLD growth (7.2 mm) of all treatments, followed by containerized Nuttall oak (6.4 mm). Containerized swamp chestnut oak on the Malone site ranked third in GLD growth but was significantly lower (3.9 mm) with bareroot swamp chestnut oak GLD growth (3.0 mm) being the least on the Malone site.

During the second growing season, the top four combinations of species/planting stock/site all included Nuttall oak. Bareroot Nuttall oak on the Malone site produced 9.3 mm of GLD growth which was significantly higher than bareroot Nuttall oak on the Carney site (7.8 mm), containerized Nuttall oak on the Carney site (7.2 mm), and containerized Nuttall oak on the Malone site (6.8 mm). None of these three combinations were significantly different from one another.

Swamp chestnut oak produced the lowest four combinations of species/planting stock/site for GLD growth during the second growing season. Bareroot swamp chestnut oak on the Carney site produced 5.1 mm of GLD growth which was not significantly different from bareroot swamp chestnut oak on the Malone site (4.6 mm). Containerized swamp chestnut oak on both the Malone and Carney sites grew 3.0 mm during the second growing season and were significantly lower than all other combinations (Table 4.25).

When combining both growing season's data to look at an overall growth pattern, Nuttall oak again produced the top four combinations of species/planting stock/site. Bareroot Nuttall oak on the Malone site grew 16.5 mm in GLD over the two growing seasons which was significantly greater than all other combinations. Containerized Nuttall oak on the Malone site produced 13.2 mm of growth, containerized Nuttall oak on the Carney site produced 11.9 mm of growth, and bareroot Nuttall oak on the Carney site produced 10.3 mm of growth. All were significantly different from one another (Table 4.25).

Swamp chestnut oak produced the lowest four combinations of species/planting stock/site regarding overall GLD growth. Bareroot swamp chestnut oak on the Malone site produced 7.6 mm of growth which was not significantly different from containerized swamp chestnut oak on

the Malone site (7.0 mm) or bareroot swamp chestnut oak on the Carney site (6.8 mm).

Containerized swamp chestnut oak on the Carney site produced 5.2 mm of GLD growth which was significantly lower than all other combinations (Table 4.25).

Table 4.25 Average groundline diameter growth by treatment and site for each growing season and overall, measured in millimeters.

Species	Planting stock/Site	2019	2020	Overall
Nuttall oak	Bareroot Carney site	2.5de*	7.8b	10.3d
	Bareroot Malone site	7.2a	9.3a	16.5a
	Conventional containerized Carney site	4.5c	7.2b	11.9c
	Conventional containerized Malone site	6.4b	6.8b	13.2b
Swamp chestnut oak	Bareroot Carney site	1.7f	5.1c	6.8e
	Bareroot Malone site	3.0d	4.6c	7.6e
	Conventional containerized Carney site	2.2ef	3.0d	5.2f
	Conventional containerized Malone site	3.9c	3.0d	7.0e

*Values in column followed by the same letter do not differ at $\alpha=0.05$.

Height Growth

Analysis of variance

The effects of site, species/planting stock, planting stock/site, species/site, and species/planting stock/site were statistically significant for height growth after the first (2019) growing season. Effects of species, planting stock, site, and species/site were statistically significant for height growth after the second (2020) growing seasons. The effects of species, planting stock, site, species/planting stock, and species/site were statistically significant for overall height growth (Table 4.26).

Table 4.26 ANOVA results for average height growth by year and overall. Bolded values are statistically significant.

Source	DF	Growing Season					
		2019		2020		Overall	
		F	P>F	F	P>F	F	P>F
(A)Species	1	0.80	0.3721	253.13	<.0001	186.64	<.0001
(B)Stock	1	2.82	0.0930	160.92	<.0001	129.07	<.0001
(C)Site	1	103.91	<.0001	126.33	<.0001	172.91	<.0001
A*B	1	38.56	<.0001	10.88	0.0010	25.52	<.0001
B*C	1	6.14	0.0133	0.13	0.7156	1.33	0.2486
A*C	1	22.50	<.0001	2.06	0.1514	8.31	0.0040
A*B*C	1	8.80	0.0030	0.59	0.4418	3.13	0.0772

Height growth variation between species

ANOVA failed to show a significant interaction of species on height growth during the first growing season ($F=0.80$, $p<0.372$), but did show a significant effect of species on height growth for the second growing season ($F=253.13$, $p<0.001$) and overall ($F=186.64$, $p<0.001$) (Table 4.26). Nuttall oak seedlings had greater height growth (13.0 cm) than swamp chestnut oak seedlings (12.6 cm) during the first growing season but were not significantly different from one another. During the second growing season, Nuttall oak (55.8 cm) grew significantly more in height than swamp chestnut oak (31.0 cm). When combining both years height growth, Nuttall oak seedlings outperformed swamp chestnut oak (68.8 cm and 43.9 cm, respectively) (Table 4.27).

Table 4.27 Average height growth by species for each growing season and overall, measured in centimeters (both sites and both planting stocks).

Species	2019	2020	Overall
Nuttall oak	13.0a*	55.8a	68.8a
Swamp chestnut oak	12.6a	31.0b	43.9b

*Values in column followed by the same letter do not differ at $\alpha=0.05$.

Height growth variation among planting stocks

ANOVA failed to show a significant interaction of planting stock on height growth during the first growing season ($F= 2.82, p< 0.093$), but did show a significant effect of planting stock on height growth for the second growing season ($F= 160.92, p< 0.001$), and overall ($F= 129.07, p< 0.001$) (Table 4.26). Bareroot seedlings had greater height growth (13.3 cm) than containerized seedlings (12.3 cm), but these values were not significantly different during the first growing season. During the second growing season, bareroot seedling grew 53.2 cm. This was significantly greater than the height growth of containerized seedlings which grew only 33.5 cm. When comparing height growth over both years combined, bareroot planting stock (66.6 cm) outperformed containerized planting stock (46.0 cm) (Table 4.28).

Table 4.28 Average height growth by planting stock for each growing season and overall, measured in centimeters (both sites and both species).

Planting stock	2019	2020	Overall
Bareroot	13.3a*	53.2a	66.6a
Conventional containerized	12.3a	33.5b	46.0b

*Values in column followed by the same letter do not differ at $\alpha=0.05$.

Height growth variation between sites

ANOVA revealed a significant interaction of site on height growth during the first growing season ($F= 103.91$, $p< 0.001$), second growing season ($F= 126.33$, $p< 0.001$), and overall ($F=172.91$, $p< 0.001$) (Table 4.26). Height growth of seedlings at the Malone site (16.2 cm) was significantly greater than height growth of seedlings at the Carney site (9.4 cm) during the first growing season. This trend continued into the second growing season as the Malone site produced 52.1 cm of height growth to the Carney site's 34.6 cm. These values were significantly different from one another. When combining both growing season's height growth, seedlings on the Malone site (68.5 cm) significantly outperformed those on the Carney site (44.2) (Table 4.29).

Table 4.29 Average height growth by site for each growing season and overall, measured in centimeters (both planting stocks and both species).

Site	2019	2020	Overall
Carney	9.4b*	34.6b	44.2b
Malone	16.2a	52.1a	68.5a

*Values in column followed by the same letter do not differ at $\alpha=0.05$.

Height growth variation by planting stock and species interaction

ANOVA revealed a significant interaction between planting stock and species in regard to height growth during the first growing season ($F= 38.56$, $p< 0.001$), second growing season ($F= 10.88$, $p= 0.001$), and overall ($F=25.52$, $p< 0.001$) (Table 4.26). MCP analysis was then utilized to determine which interactions were significant.

During the first growing season, bareroot Nuttall oak seedlings (15.5 cm) and containerized swamp chestnut oak seedlings (14.1 cm) height growth was significantly different

than containerized Nuttall oak seedlings (10.4 cm) and bareroot swamp chestnut oak seedlings (11.1 cm) (Table 4.30).

Bareroot Nuttall oak seedlings outperformed all other treatments in height growth during the second growing season with 68.1 cm of growth. Containerized Nuttall oak seedlings (43.3 cm) and bareroot swamp chestnut oak seedlings (38.3 cm) did not differ significantly in height growth. Containerized swamp chestnut oak seedlings had significantly less height growth than all other treatments and produced only 23.7 cm of height growth during year two (Table 4.30).

Combining both growing seasons' height growth shows bareroot Nuttall oak produced 83.6 cm of height growth which was significantly greater than all other treatments. Containerized Nuttall oak seedlings had the second greatest height growth with 53.9 cm, but this was not significantly greater than height growth of bareroot swamp chestnut oak (49.6 cm). Containerized swamp chestnut oak overall height growth was significantly less than all other treatments at 38.1 cm (Table 4.30).

Table 4.30 Average height growth by planting stock and species for each growing season and overall, measured in centimeters (both sites).

Species/Planting stock	2019	2020	Overall
Bareroot Nuttall oak	15.5a*	68.1a	83.6a
Conventional containerized Nuttall oak	10.4b	43.4b	53.9b
Bareroot swamp chestnut oak	11.1b	38.3b	49.6b
Conventional containerized swamp chestnut oak	14.1a	23.7c	38.1c

*Values in column followed by the same letter do not differ at $\alpha=0.05$.

Height growth variation by planting stock and site interaction

ANOVA revealed a significant interaction between planting stock and site regarding height growth during the first growing season ($F= 6.14, p< 0.013$), but failed to show a

significant interaction between planting stock and site during the second growing season ($F=0.13$, $p=0.716$) or overall ($F=1.33$, $p=0.249$) (Table 4.26). MCP analysis was then utilized to determine which interactions were significant.

Bareroot seedlings on the Malone site displayed the greatest height growth (17.5 cm) during the first growing season which was nearly double the growth of containerized seedlings (9.8 cm) and bareroot seedlings (9.0 cm) on the Carney site. Height growth of containerized seedlings (14.8 cm) on the Malone site was significantly different from all other planting stock/site combinations (Table 4.31).

During the second growing season, bareroot oak seedlings on the Malone site grew 62.3 cm in height which was significantly greater than all other combinations. Bareroot seedlings on the Carney site (44.1 cm) and containerized seedlings on the Malone site (42.0 cm) did not differ significantly in terms of height growth. Containerized seedlings on the Carney site produced significantly less height growth than all other combinations with only 25.1 cm during year two (Table 4.31).

Overall, bareroot seedlings on the Malone site grew 79.9 cm in height and were significantly different from all other combinations. Height growth of containerized seedlings on the Malone site (57.0 cm) and bareroot seedlings on the Carney site (53.4 cm) did not differ significantly. Containerized seedling height growth on the Carney site was significantly less than all other combinations with only 35.0 cm produced (Table 4.31).

Table 4.31 Average height growth by planting stock and site for each growing season and overall, measured in centimeters (both species).

Planting stock/Site	2019	2020	Overall
Bareroot Carney site	9.0c*	44.1b	53.4b
Bareroot Malone site	17.5a	62.3a	79.9a
Conventional containerized Carney site	9.8c	25.1c	35.0c
Conventional containerized Malone site	14.8b	42.0b	57.0b

*Values in column followed by the same letter do not differ at $\alpha=0.05$.

Height growth variation by species and site interaction

ANOVA revealed a significant interaction between species and site regarding height growth during the first growing season ($F= 22.50$, $p< 0.001$) and overall ($F= 8.31$, $p= 0.004$), but not during the second growing season ($F= 2.06$, $p= 0.151$) (Table 4.26). MCP analysis was then utilized to determine which interactions were significant.

Nuttall oak seedlings on the Malone site produced the greatest height growth during the first growing season (17.9 cm), followed by swamp chestnut oak on the Malone site (14.4 cm). Swamp chestnut oak height growth (10.8 cm) was greater than that of the Nuttall oak (8.0 cm) on the Carney site. All interactions were significantly different from one another (Table 4.32).

During the second growing season Nuttall oak on the Malone site produced 65.6 cm of height growth. Nuttall oak on the Carney site grew 45.9 cm in height, followed by swamp chestnut oak on the Malone site (38.6 cm), and swamp chestnut oak on the Carney site (23.3 cm). All interactions were significantly different from one another (Table 4.32).

Combining height growth of both growing seasons reveals that Nuttall oak on the Malone site significantly outgrew all other combinations with 83.5 cm of growth. Height growth of Nuttall oak on the Carney site (54.0 cm) and swamp chestnut oak on the Malone site (53.4 cm)

did not differ significantly. However, both had significantly more height growth than swamp chestnut oak on the Carney site, which grew 34.4 cm during the two growing seasons (Table 4.32).

Table 4.32 Average height growth by species and site for each growing season and overall, measured in centimeters (both planting stocks).

Species/Site	2019	2020	Overall
Nuttall oak Carney site	8.0d*	45.9b	54.0b
Nuttall oak Malone site	17.9a	65.6a	83.5a
Swamp chestnut oak Carney site	10.8c	23.3d	34.4c
Swamp chestnut oak Malone site	14.4b	38.6c	53.4b

*Values in column followed by the same letter do not differ at $\alpha=0.05$.

Height growth variation by treatment and site interaction

ANOVA revealed a significant interaction between treatment and site in height growth during the first growing season ($F= 8.80, p< 0.003$), but not during the second growing season ($F= 0.59, p= 0.442$) or overall ($F= 3.13, p= 0.077$) (Table 4.26). MCP analysis was then utilized to determine which interactions were significant.

All treatments on the Malone site displayed greater height growth than treatments on the Carney site (Table 4.33). Bareroot Nuttall oak of the Malone site produced 22.3 cm of height growth during the first growing season. This was followed by containerized swamp chestnut oak (16.1 cm), containerized Nuttall oak (13.5 cm), and bareroot swamp chestnut oak (12.8 cm), all on the Malone site. The Carney site produced height growth as follows: containerized swamp chestnut oak (12.2 cm), bareroot swamp chestnut oak (9.4 cm), bareroot Nuttall oak (8.7 cm), and containerized Nuttall oak (7.3 cm) (Table 4.33).

Bareroot Nuttall oak seedlings on the Malone site produced significantly more height growth than all other treatment/site combinations with 78.9 cm of growth during the second growing season. Bareroot Nuttall oak seedlings on the Carney site (57.3 cm), containerized Nuttall oak seedlings on the Malone site (52.4 cm), and bareroot swamp chestnut oak seedlings on the Malone site (45.6 cm) all performed similarly. Containerized Nuttall oak seedlings on the Carney site produced 34.4 cm of height growth during year two. They did not differ significantly from height growth produced by containerized swamp chestnut oak seedlings on the Malone site (31.6 cm) or bareroot swamp chestnut oak seedlings on the Carney site (30.9 cm). Containerized swamp chestnut oak seedlings on the Carney site had significantly less height growth than all other interactions with 15.7 cm of height growth during the second growing season (Table 4.33).

When both growing season's height growth are combined, bareroot Nuttall oak seedlings on the Malone site grew 101.2 cm which was significantly more than all other treatment/site combinations. Height growth of bareroot Nuttall oak on the Carney site (66.1 cm), containerized Nuttall oak on the Malone site (65.9 cm), and bareroot swamp chestnut oak on the Malone site (58.6 cm) did not differ significantly. Height growth of containerized swamp chestnut oak seedlings on the Malone site (48.1 cm) was not significantly different from the bareroot swamp chestnut oak on the Malone site, containerized Nuttall oak seedlings on the Carney site (41.9 cm), or bareroot swamp chestnut oak seedlings on the Carney site (40.6 cm). Containerized swamp chestnut oak seedlings on the Carney site had significantly less height growth than all other combinations with only 28.1 cm for the two growing seasons (Table 4.33).

Table 4.33 Average height growth by treatment and site for each growing season and overall, measured in centimeters.

Species	Planting stock/Site	2019	2020	Overall
Nuttall oak	Bareroot Carney site	8.7de*	57.3b	66.1b
	Bareroot Malone site	22.3a	78.9a	101.2a
	Conventional containerized Carney site	7.3e	34.4c	41.9c
	Conventional containerized Malone site	13.5b	52.4b	65.9b
Swamp chestnut oak	Bareroot Carney site	9.4cde	30.9c	40.6c
	Bareroot Malone site	12.8bc	45.6b	58.6bc
	Conventional containerized Carney site	12.2bcd	15.7d	28.1d
	Conventional containerized Malone site	16.1b	31.6c	48.1c

*Values in column followed by the same letter do not differ at $\alpha=0.05$.

CHAPTER V

DISCUSSION

Monthly Survival During First Growing Season

Survival was nearly perfect through May of the first growing season for all treatments on both sites. This indicates transplant shock was not an issue in this study, but other studies have reported it poses the greatest chance of seedling mortality (Waters et al. 1991). Previous studies in this sequence have experienced low containerized seedling survival which has been primarily attributed to lack of adequate protection from below-freezing weather while seedlings were in the nursery (Reeves 2016; Miles 2019; Gentry 2020). A warm 2018-19 winter likely prevented substantial loss of containerized seedlings for similar reasons in this study. Excellent bareroot seedling survival in this study is consistent with findings of comparable studies (Dowdy 2015; Hall 2017; Durbin 2018; Miles 2019).

In June of the first growing season, below average monthly rainfall and rabbit herbivory on the Carney site caused survival to decrease and it continued to decline through the growing season. Rabbits are known to target young oak seedlings and girdle them slightly above the ground (Dugger et al. 2004), sometimes causing mortality. Davis et al. (1999) also reported that droughty conditions decreased survival rates in planted oak seedlings. The combination of these two factors on the Carney site appears to have resulted in lower survival rates during the first growing season.

Malone site survival remained nearly perfect through May, until below average rainfall occurred in June and survival of containerized swamp chestnut oak began to decline. All other treatments on the Malone site stayed at or above 99 percent for the entire growing season. It is important to note that despite small declines in survival for some treatments in this study, all rates of survival are considered very good to excellent for the first growing season when implementing artificial regeneration methods for oak establishment.

Survival and Growth Performance at the end of the First Growing Season

Difference between species

Nuttall oak and swamp chestnut oak survival differed by 0.2% during the first year of this study. Seedlings of both species performed well due to their appropriateness for the sites (Table 4.11). Rushton (1988), Hodges (1994), and Rousseau (2004) discussed the importance of matching oak species to site for success of establishment. Gentry (2020) found low survival in water oak and white oak planted on a site that was too wet for either species. Although Nuttall oak is commonly found on wetter sites, both Nuttall oak and swamp chestnut oak were well suited for the well-drained soils found on both sites.

A difference in GLD growth between species utilized in this study was observed through the first growing season as Nuttall oak (5.2 mm) nearly doubled the growth rate of swamp chestnut oak (2.7 mm) (Table 4.19). This is attributed to the rapid early growth Nuttall oak produces due to its tendency to grow in areas prone to flooding. This rapid growth allows Nuttall oak to quickly grow beyond the zone of inundation in its native habitat (Reeves et al. 2016). This rapid early growth is typically associated with height growth, but it is possible that groundline

diameter growth could also be influenced due to Nuttall oak's demand for large amounts of nutrients and water to facilitate this growth.

Height growth for both species was excellent and nearly identical during the first growing season (Nuttall oak= 13.0 cm, swamp chestnut oak= 12.6 cm) (Table 4.27). This was far greater than the height growth found during the first growing season in similar studies utilizing these species (Conrad 2013; Reeves 2016; Hall 2017; Durbin 2018) and is more similar to total height growth by the end of the second growing season in those earlier studies. This is attributed to the growing conditions during the first growing season of this study as well as the sites used in this study possibly being better sites in general.

Difference between planting stocks

In this study, the slight difference in survival between planting stocks (bareroot= 96.1%), containerized= 92.9%) may be attributed to the more robust root systems associated with bareroot seedlings utilized (Table 4.12). On average, bareroot seedlings had visibly more developed root biomass at the time of planting than containerized seedlings. Davis and Jacobs (2005) found that large root volume, high root fibrosity, and an increased number of first-order lateral roots lead to improved field performance.

Containerized seedlings outperformed bareroot seedlings during the first growing season in GLD growth (containerized= 4.3 mm, bareroot= 3.6 mm) (Table 4.20). The difference through the first year in this study is attributed to the plug of nutrient rich potting soil found around the root systems of containerized seedlings as well as their seemingly excellent overall health at the time of planting. This nutrient rich soil provided a boost in growth compared to the soils native to the sites. Good health of containerized seedlings in this study may be the reason results

differed when compared to Reeves (2016) and Miles (2019) who found that bareroot seedlings displayed superior GLD growth during the first growing season. Their containerized seedlings were believed to have suffered from freeze damage in the nursery, negatively impacting performance.

Bareroot seedlings produced more height growth (13.3 cm) but were not significantly different from containerized seedling's height growth (12.3 cm) during the first growing season (Table 4.28). This slightly greater height growth associated with bareroot seedlings during the first growing season is similar to results reported by Hall (2017) but does not follow the findings of Durbin (2018) and Miles (2019). This is also contradictory to findings by Williams and Stroupe (2002) who observed less height growth in bareroot seedlings than containerized during the first year.

Difference between sites

Survival on the Carney site was lower than that of the Malone site and also between identical treatments during the first growing season. This is attributed to growing conditions associated with the Carney site in combination with earlier onset of droughty conditions. Omi (1985), Bassett et al. (2005), and Ampoorter et al. (2011) found that more compact soils reduce survival rates in seedlings. Past land use as pastureland for cattle may have resulted in compacted soil horizons which could limit both root growth and groundwater infiltration on the Carney site. Slower root growth and less available water was not an issue when rainfall was plentiful, but as the summer progressed, seedlings were likely limited by water availability and survival declined. Ampoorter et al. (2011) found that sandy soils tend to have lower soil-moisture availability than finer grained soils. Sandy soils of the Carney site would be expected to have lower water storage.

Thus, during long periods without rain, seedlings could be forced to shut down physiological processes or perhaps lack sufficient moisture to support their systems. The Malone site's silt/loam soil provided better conditions for young oak seedlings. Having previously been forest land in recent years is also thought to have aided survival. Additionally, the Carney site played host to a more competitive suite of species, primarily grasses, as opposed to the Malone site which was predominately forbs and woody competition. Despite successful herbaceous weed control, grasses on the Carney site had recolonized the treated areas by June. These grasses are very effective at utilizing any available soil moisture, further decreasing water availability for the oak seedlings.

Rabbit herbivory also played a role in survival on the Carney site. Rabbits began clipping seedlings around the same time as the onset of droughty conditions. Typically, rabbit herbivory alone would not kill an oak seedling, as they are known to resprout from their root stock when this occurs (Dugger et al. 2004). The fact that the herbivory coincided with the drought could have influenced resprouting. By the end of the growing season, rabbits had impacted 76 seedlings on the Carney site, of which only 38 resprouted.

Malone site survival showed no major impact from reduced rainfall, but containerized swamp chestnut oak seedlings did have a slight decrease. It is believed these seedlings suffered from lower survival rates due to less developed root systems and less hardy seedlings. Compared to bareroot seedlings utilized in this study, containerized seedlings did not have a large root system at the time of planting. Bareroot seedlings utilized in this study had a minimum of 10 first-order lateral roots and a strong tap root. The biomass associated with these bareroot seedlings simply could not be contained within the soil plug of the containerized seedlings used in this study. However, this alone was not enough to lower survival on this site, as containerized

Nuttall oak seedlings remained at 98.7% the entire growing season on the Malone site. It was noted that swamp chestnut oak seedlings suffered from severe desiccation and loss of their leaves during the heat of the summer, whereas Nuttall oak remained green until dormancy. It is believed that the combination of defoliation and smaller root systems resulted in lower survival of containerized swamp chestnut oak seedlings.

Seedlings on the Malone site outperformed seedlings on the Carney site when considering GLD growth during the first growing season. As previously discussed, the Malone site provided more favorable growing conditions. Though not extremely restrictive, the Carney site did have some previously-discussed characteristics that were less conducive to oak seedling growth and success.

Height growth on the Malone site (16.2 cm) was significantly greater than the height growth on the Carney site (9.4 cm) (Table 4.29). This is, again, thought to be due to growing conditions and higher competition levels of the Carney site.

Difference between treatments

Bareroot swamp chestnut oak and Containerized Nuttall oak seedlings produced the highest survival (Table 4.14). It was expected that Nuttall bareroot seedlings be the top performing treatment. However, the preference rabbits showed towards Bareroot Nuttall oak negatively impacted survival of this treatment.

Of the four treatments utilized in this study, Containerized Nuttall oak seedlings outperformed all others regarding GLD growth during the first growing season. Bareroot Nuttall oak seedlings grew the next most. The fact that these two treatments outperformed the other two is attributed to the previously discussed early growth patterns of Nuttall oak being different than

those of swamp chestnut oak. This early growth, paired with the nutrient rich plug of soil found with containerized seedlings, is considered to be the reason containerized Nuttall oak was the top performer during year one. Containerized swamp chestnut oak outgrew bareroot swamp chestnut oak in year one as well. This further supports the premise of a potential boost that containerized seedlings received from the nutrient rich soil plug.

Bareroot Nuttall oak seedlings outgrew all other treatments utilized in this study (Table 4.30). The combination of larger root biomass (when compared to containerized seedlings) and rapid early growth of Nuttall oak is thought to explain this growth. Containerized swamp chestnut oak seedlings performed similarly but not quite as well. It is believed that these two treatments produced more height growth than either bareroot swamp chestnut oak or Containerized Nuttall oak seedlings due to differing seed sources. Dudley Phelps, nursery manager for MossyOak Nativ Nurseries, explained that their acorns come from parent trees chosen specifically for acorn production and size (Phelps 2018). It is possible that these larger acorns used to grow their swamp chestnut oak seedlings allowed containerized swamp chestnut oak seedlings to be more competitive than would have been otherwise expected. Containerized Nuttall oak seedlings were expected to perform similarly to Bareroot Nuttall oak, but it is possible that rapid growth of Nuttall oak was detrimental to first year height growth in the field. It is possible the Nuttall oak root systems outgrew their containers and became pot bound. Thus, when transplanted to the field, containerized Nuttall oak seedlings may have required some time to overcome this, which reduced their ability to put on height growth during year one.

Survival and Growth Performance at the end of the Second Growing Season

Difference between species

Survival trends observed during the first growing season largely continued through the second growing season. Both Nuttall oak and swamp chestnut oak maintained high survival rates due to being appropriately matched with the sites (Rushton 1988; Gentry 2020). Less than one percentage point separated the two species. In comparable studies, Alkire (2011), Conrad (2013), Reeves (2016), and Hall (2017) all observed Nuttall oak outperforming other oak species in regard to survival when the site is suitable for the species.

During the second growing season, GLD growth of Nuttall oak (7.8 mm) was double that of swamp chestnut oak (3.9 mm) (Table 4.19). This difference is again attributed to the natural difference in early growth rates of both species (Hodges 1994; Rousseau 2004) and their need to avoid being inundated for extended periods of time (Reeves et al. 2016). Hollis (2011), Alkire (2011), Conrad (2013), Reeves (2016), and Hall (2017) all observed greater GLD growth in Nuttall oak during the second growing season as well.

Height growth during the second growing season was excellent for both species, though Nuttall oak (55.8 cm) nearly doubled height growth of swamp chestnut oak (31.0 cm) (Table 4.27). The height growth of Nuttall oak in the second growing season alone exceeded total height growth of Nuttall oak seedlings in a similar three-year study (Burkett et al. 2005) as well as total height growth of various oak species in similar two year studies (Hollis 2011; Alkire 2011; Dowdy 2015; Reeves 2016; Hall 2017; Durbin 2018; Miles 2019; Gentry 2020). This excellent height growth during year two is attributed to sites well suited for bottomland hardwood forests which were planted with appropriate species. Though seedlings received below-average rainfall during the first growing season, it was not so low that excessive dieback or mortality resulted.

Rainfall was considered to be above normal during the second growing season, based on weekly monitoring of area weather through the growing season. This allowed for the excellent height growth observed during the second growing season of this study. The difference between species can be explained by the previously discussed difference in early growth patterns. Nuttall oak is known to produce rapid early growth (Reeves 2016).

Difference between planting stocks

Bareroot planting stock outperformed containerized planting stock over the course of two growing seasons when considering survival. This is similar to findings in other recent projects (Hollis 2011; Conrad 2013; Reeves 2016; Durbin 2018; Miles 2019; Gentry 2020). This difference is again attributed to the previously-discussed more robust root systems of bareroot seedlings at the time of planting and their influence on survival (Davis and Jacobs 2005). Root systems of bareroot seedlings were so large that, in many cases, two planting slits side by side were necessary to facilitate planting, even when using eight-inch-wide planting shovels.

Bareroot seedlings (6.7 mm) outgrew containerized seedlings (5.0 mm) in GLD growth during the second growing season (Table 4.20). This is opposite of what occurred in the first growing season when containerized seedlings performed better. Hall (2017) and Conrad (2011) also observed greater containerized GLD growth in year one and greater bareroot GLD growth in year two. The reversal from year one to year two in this study is attributed to the fact that the soil plug associated with containerized seedlings is likely not as influential on GLD growth. At that point, new roots should have reached out beyond that soil plug resulting in similarity between planting stocks as they absorb nutrients from similar soil with similar nutrient availability. It is probable that most of the nutrients in the soil plugs had likely been absorbed in year one.

Additionally, while bareroot seedlings had more extensive root systems at planting, they had to recover from transplanting and establish new root growth during the first growing season. Once containerized seedlings lost the competitive advantage of the nutrient rich soil plug and bareroot seedlings had established new growth on a larger root system, bareroot seedlings produced more GLD growth.

A large difference between height growth of bareroot and containerized seedlings was observed during the second growing season (Table 4.28). This is consistent with findings from the first growing season of this study, but the difference was much greater for year two. The reason for this difference is the same as was presented in the previous paragraph regarding GLD growth. Bareroot seedlings outgrowing containerized seedlings during year two was also observed by Durbin (2018) and Gentry (2020) but is contradictory to Hall (2017) and Miles (2019), where containerized seedlings exhibited more height growth during the second growing season.

Difference between sites

The difference in survival rates between sites increased slightly during the second growing season. Survival on the Carney site fell below 90% overall and was significantly lower than survival on the Malone site. The difference between sites was again attributed to the Carney site's slightly less favorable growing conditions.. It should be mentioned that survival was still excellent for artificial oak regeneration efforts. Nuttall oak and swamp chestnut oak are naturally found in floodplains near one another, with Nuttall oak growing on less well-drained flats and swamp chestnut oak growing on more well-drained flats (Rousseau 2004). The fact that both

species survived well, despite statistical difference, is support of the sites being well suited for bottomland oak establishment.

The difference in sites observed for the first growing season was seemingly nonexistent during the second growing season. Statistically, the sites performed the same, with the Malone site producing only 0.2 mm more GLD growth than the Carney site during year two (Table 4.21). The fact that seedlings on both sites performed similarly in year two is believed to be a result of (1) well-established seedlings from year one and (2) favorable growing conditions during the second growing season. At the time of second year measurements in late September 2020, there was standing water in many areas on both sites. This was not the case at the time of first year measurements in early October 2019. No rain gauge was utilized in year two, but it is believed that both sites received substantially more rain during the second growing season, as observed by weekly monitoring of area weather through the growing season. Surrounding vegetation was still very green at the time of second year measurements, which indicates favorable soil moisture during the growing season. The availability of water throughout the growing season on both sites reduced negative effects of sandy, compacted soils and more intense herbaceous competition on the Carney site. Despite less favorable growing conditions, frequent rains through the summer allowed seedlings on the Carney site to perform as well as those on the Malone site. Conrad (2011) also observed a large difference in GLD growth between two sites in year one and no difference in year two, possibly due to seedlings being more well established by year two.

Similar to the first growing season, seedlings on the Malone site outgrew their counterparts on the Carney site (Table 4.29). This is again attributed to less favorable growing conditions of the Carney site compared to the Malone site.. A similar study by Hall (2017) observed less than half the height growth by seedlings when compared to this study.

Difference between treatments

Of the four treatments utilized in this study, bareroot swamp chestnut oak exhibited the highest survival rate. It is believed Bareroot Nuttall oak would have exhibited a similar survival rate had the previously-discussed rabbit herbivory not occurred. Containerized Nuttall oak seedlings produced the second highest survival rate while swamp chestnut oak of the same planting stock had the lowest survival. Had rabbits not impacted survival, it is likely that bareroot seedlings of both species would have outperformed containerized seedlings of both species.

Bareroot Nuttall oak seedlings outperformed all other treatments during the second growing season when considering GLD growth (Table 4.22). Containerized Nuttall oak seedlings grew the next most. These two treatments reversed from the pattern of the first growing season, likely due to reduced nutrient availability of the soil plug associated with containerized seedlings. Both treatments nearly doubled growth observed in either swamp chestnut oak treatment, which is further evidence of Nuttall oak's superior early growth rates. The combination of rapid early growth of Nuttall oak and the larger root mass of the bareroot explain this treatment's top performance. Bareroot swamp chestnut oak seedlings grew the third most of all treatments during the second growing season, followed by containerized swamp chestnut oak seedlings. Again, the planting stocks for swamp chestnut oak reversed from the first growing season as observed in Nuttall oak, with bareroot producing better results in year two.

Bareroot Nuttall oak seedlings outgrew all other treatments during the second growing season, nearly tripling the growth of containerized swamp chestnut oak seedlings (68.0 cm and 23.7 cm, respectively), which had the least height growth (Table 4.30). The excellent growth of Bareroot Nuttall oak is believed to be caused by the combination of factors previously described

for GLD growth. Containerized Nuttall oak seedlings produced the second greatest height growth during the second growing season, also likely due to the species' rapid early growth. Bareroot swamp chestnut oak seedlings performed similarly to Containerized Nuttall oak seedlings but had slightly less height growth in year two. Again, this is thought to be due to slower early growth rates of swamp chestnut oak as compared to Nuttall oak. Containerized swamp chestnut oak produced the least height growth of all treatments, likely due to slower growth rate and smaller root systems at planting.

Overall Growth Performance

Difference between species

When adding the two growing season's data together to analyze overall growth patterns, Nuttall oak GLD growth is greater than that of swamp chestnut oak. Nuttall oak produced nearly twice as much GLD growth as swamp chestnut oak over the course of this study (Table 4.19). Reasons for this have been discussed previously. Rousseau (2004) states that Nuttall oak is often found on less well-drained flats and ridges of minor bottoms whereas swamp chestnut oak is often found on more well-drained flats. Considering the amount of standing water on both sites at the time of second year measurements, these sites may have been too wet for swamp chestnut oak and better suited for Nuttall oak. These findings are similar to that of Hollis (2011), Alkire (2011), Conrad (2013), Reeves (2016), and Hall (2017) who observed greater overall GLD growth by Nuttall oak in their studies.

Overall height growth of both Nuttall oak and swamp chestnut oak seedlings exceeded the two-year growth of oak species in similar studies (Burkett et al. 2005; Hollis 2011; Alkire 2011; Dowdy 2015; Reeves 2016; Hall 2017; Durbin 2018; Miles 2019; Gentry 2020). In this

study, Nuttall oak seedlings outperformed swamp chestnut oak seedlings when both growing season's data were combined (Table 4.27). This is identical to findings reported by Hollis (2011), Alkire (2011), Reeves (2016), and Hall (2017) in which Nuttall oak seedlings produced more height growth than other species during two-year studies.

Difference between planting stocks

Bareroot planting stock produced the most GLD growth overall in this study (Table 4.20). Overall better GLD growth by bareroot seedlings is attributed to the observably larger root mass at the time of planting with subsequent new root development. This difference was not recognized in first-year results, as containerized seedlings probably received a boost to GLD growth by the soil plugs they were grown in. By the second growing season, nutrients in these plugs were probably consumed and fibrous roots of seedlings had reached well beyond the plugs drawing nutrients from soils on the site. Both planting stocks were drawing nutrients from the same soil, so the larger root mass of bareroot seedlings provided an advantage. Bareroot seedlings have been shown to produce more GLD growth than containerized seedlings in previous studies (Alkire 2011; Durbin 2018; Miles 2019).

Bareroot seedlings outperformed containerized seedlings in regard to height growth over the course of this study. This difference is again attributed to more extensive root systems possessed by bareroot seedlings at planting and subsequent root development. Hollis (2011), Alkire (2011), Conrad (2013), Reeves (2016), Hall (2017), Durbin (2018), and Gentry (2020) also observed more height growth by bareroot seedlings compared to containerized seedlings over the course of their studies.

Difference between sites

Over the course of this study, the Malone site produced better GLD growth than the Carney site. This is attributed to previously-discussed differences between the sites.

The Malone site also produced better height growth than the Carney site during both growing seasons and overall. Variation between or among sites is not unusual. It can even exist within a site, or along an individual row of seedlings, when hardwood seedlings are involved (Hodges 1994). This, coupled with genetic variability, increases variability in expected performance of hardwood seedlings (Rousseau 2017b).

Difference between treatments

After two growing seasons, Bareroot Nuttall oak was the top performing treatment in terms of GLD growth. Containerized Nuttall oak seedlings produced the second most growth, followed by bareroot swamp chestnut oak and containerized swamp chestnut oak seedlings. This is further evidence of the impact Nuttall oak's inherent early growth rates had on the results of this study. Bareroot planting stocks associated with each species performed better than containerized planting stock, again highlighting differences between planting stocks previously discussed.

Bareroot Nuttall oak produced the most height growth of the four treatments used, followed by Containerized Nuttall oak seedlings, bareroot swamp chestnut oak seedlings, and containerized swamp chestnut oak seedlings (Table 4.30). Regardless of planting stock, Nuttall oak seedlings outperformed swamp chestnut oak seedlings. This also illustrates the difference between planting stocks, as bareroot seedlings of both species outperformed containerized seedlings of the same species.

CHAPTER VI

CONCLUSIONS

Bareroot seedlings exhibited superior growth and survival and can be considered an economically viable option for artificial oak regeneration in southern Mississippi. This study supports findings of others who have observed that when competition is controlled during the first growing season, high-quality 1-0 bareroot seedlings can exhibit satisfactory (80-90%) to excellent (90%+) survival and growth that is comparable to or better than containerized seedlings (Mullins et al. 1998; Sweeney et al. 2002; Ezell et al. 2007; Hollis 2011; Conrad 2013). Containerized seedlings exhibited acceptable growth and survival and may be of greater value on marginal sites (Teclaw and Isebrands 1993; Burkett and Williams 1998; Williams and Stroupe 2002). On sites conducive to growth of bottomland hardwood species, bareroot seedlings provide the best and most cost-effective opportunity for establishing an oak stand.

Nuttall oak produced survival equal to or better than swamp chestnut oak and better GLD and height growth over a two-year period. Nuttall oak may be a top contender for artificial regeneration for landowners seeking faster-growing oak species. However, it is important to consider site characteristics when selecting species to regenerate a site (Hodges 1994). Planting a species not adapted to a particular site can result in complete failure in extreme cases.

Unforeseen circumstances, such as the rabbit herbivory observed in this study, can play a role in stand success. Even when seedlings are properly planted and successful herbaceous weed control is implemented, unforeseen factors can reduce survival and growth (Reeves et al. 2016).

While unpredictable, these factors reinforce the importance of obtaining vigorous seedlings, utilizing proper planting techniques, and controlling vegetative competition in these stands.

This study is applicable to landowners and land managers with the objective of establishing Nuttall oak and swamp chestnut oak on sites amenable to bottomland hardwoods with similar soils and expected growing conditions as those in this study.

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