The Effects of Mechanical Site Preparation Treatment and Species Selection on Survival and Carbon Pools in 12-Year-Old American Sycamore (*Platanus occidentalis*) and Willow Oak (*Quercus phellos*) Riparian Plantations in the Southeastern U.S Piedmont

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Abstract

Riparian wetlands may provide numerous ecosystem services, including water quality protection, food and fiber supply, wildlife habitat, and carbon sequestration. In recent years, riparian forests have received increased attention and funding for riparian forest restoration projects. Unfortunately, failures of riparian restoration efforts are likely due to mortality of planted trees. Tree mortality is commonly attributable to several factors, including selection of species that are not well suited to the wetland sites, inadequate planting densities, soil compaction associated with former agricultural activities, lack of microtopographic relief that allow small seedling to survive on wet sites, competition by herbaceous plants, and browse. Selection of well-suited species, dense planting and use of mechanical soil site preparations are all potential remedies to partially address success of wetland restoration plantings. Riparian restoration projects have historically been undertaken with goals of improving water quality and/or wildlife habitat, but in recent years there has been increased valuation of carbon sequestration. Carbon valuation appears to be increasing, but more research is needed to determine rates and pools of carbon accumulation in riparian areas. Our research quantifies forest establishment effects on multiple carbon pools in a densely planted, 12-year-old old-field riparian restoration. Our research evaluated the effects of four soil mechanical site preparations (bed, disk, pit, and mound and rip) and species selection (American sycamore (*Platanus occidentalis*) and willow oak, (*Quercus phellos*) on forest establishment and carbon storage across multiple pools, namely in planted trees, herbaceous vegetation, fine roots, organic soil horizons, and the mineral soil. At 12 years, we found that species selection was more important to carbon storage than site preparation. American sycamore was well suited to the site and had better survival than willow oak (64% vs 42% survival). American sycamore also stored more carbon across all site preparations than willow oak. Measured carbon storage averaged 74.8 Mg ha-1 for American sycamore treatments and 63.1 Mg ha-1 for willow oak treatments. The plots were densely planted (1.2 m (4ft) by 1.8 m (6ft) spacing), and forests were established even in higher mortality willow oak plots. These results indicate that high planting density is potentially a viable practice for establishing riparian forest cover, especially if desired species are marginally site suited or other survival inhibiting factors exist.

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General Audience Abstract

Riparian forests located within the floodplain of streams are known to protect stream water quality, provide wildlife habitat, and store carbon. Due to these benefits, trees may be replanted on riparian areas that were formerly used for agriculture. Unfortunately, trees planted on these restoration sites have often died. The tree mortality may be due to planting incorrect tree species that may struggle on wet floodplains, soil compaction from agricultural practices, not enough trees being planted, and restored floodplains lacking small, elevated areas common across natural wetlands known to favor tree rooting and survival. Reasonably, selecting species that are well suited to a specific site, planting trees more densely, and using plowing methods designed to break up compaction and create some relief in elevation would amend these issues. Traditionally, floodplain restorations have focused on improving water quality and providing habitat for wildlife, but the benefits of storing carbon have become increasingly valuable in recent years. While we know that wetlands store carbon, research is needed to examine how quickly and where carbon is stored. Our research quantifies forest establishment and carbon storage of very densely planted, 12-year-old American sycamore (*Platanus occidentalis*) and willow oak (*Quercus phellos*) plantations. This research examines the effects four soil tillage methods and tree species selection had on tree survival and carbon storage. Carbon storage was measured in vegetation, soil, and small roots. Twelve years after planting, species selection had a greater impact on carbon storage than soil tillage methods. No tillage method altered survival or total carbon after 12 years, but American sycamore was found to have better survival and more carbon than willow oak in all soil tillage treatments. Both species were successful in establishing planted forests on the floodplain, but the success was aided by the very high initial numbers of planted trees that ensured enough trees would survive on the site even after trees were lost to mortality. Creation of willow oak forests benefitted more from dense planting, as it was less suited to the site and more planted willow oaks died. We recommend tillage for compacted soil, selecting the most suitable tree species, and planting adequate numbers of trees.

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Table of Contents

Chapter 1: Riparian Wetland Restoration Challenges and Potential Solutions

Background

Forested wetlands are known to improve water quality, sequester carbon, and produce food, fiber, and timber (Stelk and Christie, 2014). Wetlands were historically drained and transitioned into other land uses, leading to global loss of approximately 50% since 1700, reducing wetland ecosystem services (Davidson, 2014). Wetlands in the United States gained federal protection in 1987, due to inclusion within the Federal Water Pollution Control Act of 1972 (Clean Water Act) (Deland, 1992). Under current federal policy, drainage or disturbance of a wetland requires restoration, creation, or enhance of an equal or greater area of similar wetland classification. This "No Net Loss of wetlands" policy and other water quality and wildlife enhancement programs have caused an increase in wetland restoration activities, including restoration of riparian wetland forests.

Riparian forests are types of wetland ecosystems, characterized by their position within stream and river floodplains that are dominated by an overstory tree cover. Riparian forests are also known as bottomland hardwoods, floodplain forests, forested wetlands, and riparian buffers. Riparian forests are very effective at improving water quality by trapping eroded sediment, trapping and/or transforming excess nutrients, shading the stream against thermal increases, and providing food and woody habitat to the stream (Stelk and Christie, 2014). Riparian forests are also sources of forest products, including both solid wood products and fiber. High available soil moisture, alluvial deposits of nutrient rich soils, and flood water creation of varied topography across floodplains allow riparian forests to be diverse and productive ecosystems (Hodges, 1997). Federally funded programs, such as the Conservation Reserve Program and the Wetland

Reserve Program, were created to promote riparian forest restoration on agricultural land to sequester carbon, improve water quality, and provide wildlife habitat (Bradburn et al, 2010).

Despite increased attention and federal funding, failures of riparian forest plantings are common. Past restorations had failure rates as great as 90% (Stanturf et al, 2001). On restorations sites overseen by federal agencies, failure is judged by high mortality of planted trees thus failing to meet recommended surviving stem densities. Commonly cited causes for failures include poor site suitability of planted species, soil compaction on former agricultural lands, and lack of microtopographic relief present on less disturbed floodplains (Bailey et al, 2007, Gardiner et al, 2001). Proposed solutions include better species selection, dense planting, and use of soil mechanical site preparation treatments to alleviate compaction and mimic natural microtopography. Site preparations intended to create varied topography, such as mounding or bedding, are common and effective practices on industrial forestry plantation on wet sites across the southeastern U.S., but these techniques have seen slow acceptance within riparian restorations (Löf et al, 2012, Self et al, 2012, Neaves et al, 2017).

Carbon sequestration is a natural function within riparian wetlands, due to their high productivity and hydroperiods that slow soil decomposition and lead to large carbon storage potential (Dybala et al, 2019). Riparian carbon is stored in several pools (Bansal et al, 2023). Aboveground pools include woody plants and herbaceous plants, and belowground pools include organic and mineral soil horizons, roots, and microbial soil populations. While studies have examined the effects of site preparation treatment and species on success of planted tree survival and growth (Self et al, 2012, Simmons et al, 2012, Steele et al, 2021), research focused on impacts of site preparation on multiple pools and total carbon storage is limited. This research is

designed to quantify the impact of species selection and site preparation treatments on 12-year plantation establishment, as well as to quantify carbon storage across multiple pools.

Research and Objectives

In 2011, Curtis et al. (2015) planted a riparian plantation near Critz, VA. The plantation was planted with American sycamore (*Platanus occidentalis*) and willow oak (*Quercus phellos*) at very high densities due to space limitations for the original experiment (~4,500 ha^{-1}). American sycamore is fast growing pioneer species common to riparian areas, while willow oak is a slower growing, mid-successional floodplain species. Both species were selected due to their natural occurrence within floodplains in Virginia and common use in riparian plantings. Four soil mechanical site preparation treatments (bedding, disking, pit and mounding, and ripping) were used. All four treatments are designed to reduce compaction, although the effects vary in soil depth affected. In addition to reducing soil compaction, bedding and pit and mounding also provide microtopographic relief. Steele (2020) and Curtis et al. (2015) focused on impacts of treatments on survival and growth of American sycamore and willow oak through four years post planting.

Twelve growing seasons after the initial planting, the current study collected new data within the original site. As previously, measurements included survival, total height, and diameter of planted trees. The scope of research was simultaneously expanded to include carbon pools and only considered the site preparation treatments, while disregarding planting aids and planting sources that were equally spread within the site preparation treatments. Carbon measurements were obtained for planted trees, herbaceous vegetation, organic soil horizons, fine roots, and mineral soil. The objectives of these measures were to determine 12-year effects of site preparations on multiple pools of above- and below-ground carbon, planted tree survival in

both species, and to compare American sycamore and willow oak effectiveness at carbon storage and riparian forest establishment.

Thesis Organization:

This thesis is divided into four chapters. Chapter 1 provides a general background which describes riparian restorations efforts, common causes of restoration failure, potential solutions, introduces site establishment and past site research, introduces study objectives, and outlines the thesis organization.

Chapter 2 provides and discusses the 12 year effects of site preparation treatments on American sycamore survival and carbon storage on a riparian restoration site. The objective of Chapter 2 is to evaluate impacts of mechanical site preparation treatment on survival and carbon storage across multiple pools in American sycamore plantings. Planted American sycamore survival and carbon storage, as well as carbon storage of herbaceous vegetation, fine roots, organic soil horizons, and mineral soil are compared across four site preparation treatments (bed, disk, pit and mound, rip). Statistics are reported and discussed for aboveground, belowground, and total measured carbon storage of sycamore plantings.

Chapter 3 discusses the 12-year effects of site preparation treatments upon willow oak planted to restore an old-field to a riparian forest restoration. The objective of Chapter 3 is to quantify impacts of site preparation treatment on survival and carbon storage across multiple pools in willow oak plantings. Planted willow oak survival and carbon storage, as well as carbon storage of herbaceous vegetation, fine roots, organic soil horizons, and mineral soil are compared across four site preparation treatments (bed, disk, pit and mound, rip). Statistics are reported and

discussed for each treatment's aboveground, belowground, and total carbon storage on willow oak plots.

Chapter 4 discusses and contrasts American sycamore and willow oak effectiveness for restoring the riparian forest and sequestering carbon. The objectives of this chapter were to compare the survival and carbon storage of American Sycamore and willow oak plantings and to evaluate the effectiveness of species selection on riparian reforestation success.

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Chapter 2: Carbon Pools and Survival of 12-Year-Old American Sycamore (*Platanus occidentalis*) Plantations as Affected by Four Site Preparation Treatments

Abstract:

American sycamore (*Platanus occidentalis*) is a fast-growing pioneer species that is well adapted to certain riparian sites; thus, it is commonly selected for riparian restorations. Different site preparation treatments may benefit establishment, but the long-term effects are uncertain. Additionally, carbon storage is becoming increasingly important, but there is little information regarding total carbon storage in riparian restorations. This study was designed to quantify carbon storage as influenced by site preparation treatments (pit and mound, bed, rip, disk) in 12-year-old American sycamore plantations. Carbon was measured in planted trees, herbaceous vegetation, fine roots, organic soil horizons, and mineral soil. Results indicate soil carbon pools contain over 50% of all stored carbon but were little affected by site preparation. Carbon storage was greatest in the mineral soil, followed by the planted trees. Other measured pools were negligible compared to mineral soil and planted trees. Soil mechanical site preparation was not found to significantly impact total carbon storage in the measured pools. All plots were successful in establishing an American sycamore dominated overstory.

Introduction:

Wetlands offer an array of ecosystem services including wildlife habitat, food and fiber resources, and water quality protection (Stelk and Christie, 2014). Despite providing such important services, wetlands have historically been undervalued by humans (Stelk and Christie, 2014), leading to an estimated 50% reduction in area globally since 1700 CE (Davidson, 2014). Beginning in 1987, reduced wetland ecosystem services led to the inclusion of wetlands under the Clean Water Act of 1972, leading to preservation and restoration efforts and the federal policy of "No Net Loss of Wetlands" (Deland, 1992).

The fertile alluvial soils, available moisture, and gentle terrain made riparian forests attractive for agricultural conversions for native Americans and European colonists. Currently, riparian restorations commonly occur on previously converted agricultural, and such efforts are favored by state and federal programs in Virginia as former wetlands logically provide better restoration sites than non-wetlands (Bradburn et al., 2010). Although riparian programs are often

created with the stated goals of protecting water quality and creating wildlife habitat, restoring riparian wetlands also creates carbon sinks. Riparian forests have been modeled to contain 68-157 Mg C ha^{-1} in aboveground vegetation (Dybala et al, 2018), rivaling carbon storage in the most productive forest ecosystems. Furthermore, restored riparian forests have been shown to accumulate carbon at twice the rate of non-forested riparian areas (Dybala et al, 2018), showing that carbon storage is another positive consequence of riparian forest restorations.

. Carbon accumulation in riparian restorations is influenced by multiple factors, including the productive nature of alluvial soils coupled with the abundant moisture of the wetland sites, and the anaerobic nature of portions of the floodplains. Soils in wetlands are often saturated by water, thus wetland soils are often anaerobic, which can favor carbon storage. In the absence of oxygen, decomposition happens very slowly (Davidson & Janssens, 2006), thereby leading to a higher rate of accumulation of organic matter than drier soils (Krauss et al., 2021).

Restored and created riparian forests provide valuable ecosystem services; however, successful wetland restoration projects are not assured (Mathews and Endress, 2008). Common past failures of wetland restoration led to the development of a required 2:1 ratio for wetland restoration, meaning that permitting requires that twice as much area of forested wetland be restored or created to offset disturbance (Brown & Lant, 1999). Failures in establishing forests on restoration sites have been largely attributed to failures in planted tree survival, due to multiple causes. Low survival can be caused by poor planting techniques, incorrect species selection, herbaceous competition, soil compaction limiting root growth, animal browse, and unnaturally low levels of microtopography (Gardiner et al, 2001, Bailey et al, 2007).

Proper species selection is important for successful restoration, particularly with regard to site hydrology (Bailey et al, 2007). Often species will be selected for perceived wildlife value

rather than suitability to the site. Poorly selected species struggle with wet site conditions, and shrubs and slow growing species may not have sufficient height growth rates to compete effectively with robust hydrophytic herbaceous plants. American sycamore (*Platanus occidentalis*) is an early successional species, favoring full light and rapid early growth. Sycamore is a common pioneer species in wetlands of the Eastern United States (Wells and Schmidtling, 1990). Sycamore tolerates somewhat poorly drained soils and is common in elevated alluvial areas, such as natural levees along streams (Wells and Schmidtling,1990).

Sycamore's status as a rapid-growth, pioneer riparian species allows it to be a viable species for planting in deforested riparian areas with the goals of establishing forest cover and biomass quickly (Davis and Trettin, 2006). Although American sycamore may not favor wildlife due to hard mast production, its ability to quickly establish forest cover is beneficial to wildlife for stratified cover and nesting sites (Stanturf et al, 2001). Wildlife research has indicated that including large numbers of fast growth pioneer species in riparian plantings can improve avian habitat by achieving rapid establishment of forest cover (Twedt et al, 2002). Slower growing mast producers such as oak may be better for specific wildlife species, yet planting faster growing species was found to benefit a greater total number of avian species. Sycamore's rapid growth relative to other species has been measured and noted in several studies, including initial previous measures at our research site (Davis and Trettin, 2006, Curtis et al, 2015, Steele et al, 2021). The rapid growth of American sycamore also makes it attractive to restoration managers who have to show adequate height growth of planted trees on restoration sites.

In natural riparian wetlands, small changes in surface elevation, or microtopography, are created by sediment deposition, erosion, fallen-tree root pits and mounds, and animal activity (Bruland & Richardson 2005). Microtopography creates variation in elevation and hydroperiod

across a wetland (Stanturf et al, 2001). These elevation differences allow trees with different hydroperiod tolerances to preferentially survive on elevated areas across the site (Stanturf et al, 2001). Microtopography has been found to significantly impact the structure and moisture content of the soil, impacting the distribution of seedlings and species (Hodges 1997; Giese et al. 2000). American sycamore is impacted by floodplain topography, favoring moderately well to somewhat poorly drained levees, ridges, and sometimes flats with better drainage over poorly and very poorly drained sloughs and depressions (Hodges, 1997). Such soil drainage preferences indicate that site preparation could be used to create microtopography that would favor establishment of American sycamore on wet sites.

Due to the previous tillage and traffic of former agricultural lands selected for riparian restoration, compaction, and homogenization of microtopography are commonly found on riparian restoration sites. Mechanical site preparation involves the use of mechanized equipment to amend soil conditions to favor establishment of desired tree species, by ameliorating soil conditions, creating better planting condition, and reducing competition (Aust et al. 2020). Because many wetland restorations occur on former agricultural lands having compacted tillage induced layers or “plow pans”, site preparation can be useful to reduce soil compaction. Gardiner et al. (2000) found that on former agricultural sites, fast growing species such as American sycamore generally need plowing to a depth of 40-50 cm to break up plow pans, allowing for increased drainage and rooting. Mechanical site preparation can also be used to manipulate the depth of the water table relative to planted trees root systems on wetland sites (Morris and Lowery, 1988). Forest managers have effectively used mechanical site preparation, such as bedding to reduce soil compaction and create microtopography on wet sites since the 1950s and such efforts have been found to increase early planting survival and growth (Miwa et al. 2004).

Some of the more common site preparation treatments on wetland sites include ripping, disking, bedding, and mounding (pit and mounds).

Both ripping and disking are common site preparation activities in forestry, intended to reduce soil compaction. Ripping increases aeration and water infiltration by shattering hardpans in the soil. Ripped treatments have been shown to increase seedling survival by removing obstacles to root establishment (Löf et al. 2012). Ripping is achieved by using a chisel plow or ripping shank that is pulled through the compacted soil horizons to depths up to 0.5 m. Disking provides benefits similar to ripping but is generally limited to shallower soil depths than ripping (Moser et al. 2009). Disking utilizes gang disk plows rather than chisel plows. Another potential benefit of disking is short term physical removal of herbaceous vegetation on the site, thus reducing initial competition (Barry et al). Neither ripping or disking alters the relative depth of the water table compared to ground level (Löf et al. 2012, Morris and Lowery 1988).

Mounding is a forestry practice that is used on poorly aerated soils that have a high-water table. Mounding is more commonly associated with establishment of bottomland hardwoods on wetland sites (Löf et al. 2012) or on poorly drained sites in the northeastern US or Canada (Londo and Mroz, 2001, Thiffault et al, 2020). Sometimes an excavator, backhoe, or specialized mounder is used to create both a pit and mound. The soil from the pit is piled into a mound adjacent to the pit, thus simultaneously creating both higher and lower microsites. This practice is intended to mimic root tip-up mounds and pits that occur naturally from trees being uprooted (Löf et al. 2012). Mounding incorporates soil organics, decreases compaction, and creates both areas with increased and decreased depths to the water table. This duality of wet and dry microsites potentially allows for greater diversity of species, as hydrologic regime changes dramatically in riparian areas due to subtle changes in elevation (Hodges 1997, Ott et al. 2020).

Previous research has indicated that use of mounds on wet sites can enhance survival and growth of American sycamore, but American sycamore planted in pits had lower early survival and growth (Steele et al, 2021).

Bedding is a mechanical site preparation treatment that creates linear elevated areas, or beds. Similar to mounding, bedding increases the relative depth to the water table for planted seedlings and increases the volume of non-saturated soil available for seedling rooting (Miwa et al. 2004). Bedding is widely used for establishment of pine plantations across the southeastern coastal plain as bedding increases the initial survival of plantings, and it is widely applied on poorly-drained wet mineral flats (Jones et al. 2010). Bedding also reduces soil compaction while creating raised microtopography. Reduced compaction and greater water table depth have led to use of bedding to establish plantations on sites with poorer drainage and higher water tables (Löf et al. 2012). Numerous research studies have concluded that raised microtopography on wetter industrial plantations have increased survival and early growth of the planted trees (Miwa et al. 2004, Self et al 2012), but also indicate that the growth difference due to treatments may diminish as the stand ages (Neeves et al. 2017, Lang et al. 2016). While forestry operation research has largely focused on commercially important species such as loblolly pine (*Pinus taeda*) and slash pine (*Pinus elliottii*) (Self et al, 2012), site preparation treatments which created microtopography on wet sites have consistently led to improved survival and initially larger trees (Pritchett 1979, McKee 1985, McKee and White 1986, Aust et. al. 1998, Neaves et al. 2017).

Justification/Objectives:

Carbon storage is a potentially important biproduct of riparian restoration efforts and may become increasingly valuable on restoration sites. Therefore, it is advantageous to acquire additional information about the degree to which riparian forest restoration strategies and

techniques can impact carbon in riparian forests. Also, an understanding of where carbon is accumulated and stored in the aboveground and belowground pools may also allow wetland managers to make more informed decisions on manipulations of carbon storage for a particular species or site. Site preparation treatments are known to increase early survival and growth of plantings, but research is generally limited to seedling early phases and rarely directly compares the impacts of different soil treatments or measures multiple pools of carbon over a longer period.

Our research quantified the impacts of four site preparation treatments on planted American sycamore survival, as well as documenting how five above-ground (tree and shrub strata) and below-ground (litter, roots, mineral soil) carbon pools are impacted. This research follows that of Curtis et al. (2015) and Steele et al. (2021) by assessing the site and stand responses 12-years after the initial treatments and plantings. Previous research by Steele et al. (2021) and Curtis et al. (2015) focused on survival and early growth of American sycamore and willow oak riparian plantings using whole plots of site preparation treatments and equally replicated subplots including a variety of planting stock and planting aid treatments. Our study collected survival and growth data 12-years post planting in the American sycamore plots but focused only on the carbon storage effects of the four mechanical site preparation treatments (bed, disk, pit and mound, and rip). Specifically, our research addresses the following objectives:

Objective 1. Determine mechanical site preparation treatment effects on the above- ground carbon stored in American sycamore plantings. The above-ground pool includes planted trees and herbaceous vegetation and addresses the following null hypothesis.

1) H0: Mechanical site preparation treatments do not alter above-ground biomass for American sycamore.

Objective 2. Determine mechanical site preparation treatment effects on below-ground carbon pools stored in riparian plantings of American sycamore. Belowground pools include litter layers (organic soil horizons), fine roots, and soil carbon. These analyses will address the following hypothesis.

2) H0: Mechanical site preparation treatments do not alter below-ground biomass for American sycamore.

Objective 3. Determine mechanical site preparation treatment effects on total carbon stored across total above- and below-ground carbon pools and address the following hypothesis

3) H0: Mechanical site preparations will not affect total carbon storage of plots at 12-years post planting.

Objective 4. Quantify the survival of planted American sycamore across four mechanical site preparation treatments in a riparian restoration via the following hypothesis.

4) H0: Mechanical site preparations do not alter the survival of American sycamore plantings at 12 years.

Methods

Study Site Description and Treatment Layout:

The riparian study site (centered at N36^{o}37’18”, W80^{o}08’42”) is located within the Virginia Tech Reynolds Homestead Forest Resources Research Center. The Reynolds Homestead is a 280-hectare research and outreach facility operated by Virginia Tech in the Piedmont region

of Patrick County, Virginia (Figure 2.1). In the 1800s, it was managed as a tobacco plantation by the R.J. Reynolds family in the uplands, and other agriculture such as corn in the bottomlands (Steele et al. 2021). The riparian zone of the site is located on the eastern floodplain of an unnamed, first order tributary approximately 400 m before it merges with Mill Creek. The watershed above the riparian restoration is approximately 512 ha based upon United States Geological Survey (USGS) StreamStats website. Steele et al. (2021) reported the soils series to be French and Braddock series. Steele also noted that the soils range from somewhat-poorly to moderately-well drained, and the soil profiles evidenced past land clearing (buried profiles) and agriculture (hardpans). The floodplain is active, with approximately 25 cm of flooding occurring in most spring seasons (Curtis et al. 2015). On-site personnel report 1-2 floodplain submergences in normal years (Steele et al. 2021). Past disturbances include agricultural operations and forestry experiments. The original riparian restoration study was planted in May 2011 to evaluate survival and growth of American sycamore and willow oak (*Quercus phellos*) using 60 combinations of planting treatments, including regeneration sources, planting aids, and site preparation treatments. We have reduced the scope of the research to an evaluation of the whole plot site preparation treatments (disk, rip, bed, pit and mound), each of which includes the equal replication of the original suite of planting aids and planting sources. Also, our research will focus on site preparation treatment effects on carbon storage in the riparian American sycamore plantation with less focus on the original silvicultural evaluations of survival and growth parameters.

After 12 growing seasons, the study area is an established American sycamore plantation (Figure 2.2) with four mechanical site preparation treatments. There are five American sycamore blocks in the study area. Each block is 0.0429 hectares and contains each of the four site

preparation treatments applied: bedding, disking, pit and mounding, and ripping. Each replication has 4 rows of 12 trees per site preparation treatment. Since area was limited in the original study, the trees were planted on a closer spacing of 4 ft (1.22 m) * 6 ft (1.83 m), which translates to a planting density (~4,500 trees Ha^{-1}) approximately 4x higher than normal for typical forest operations yet may be beneficial to ensure riparian establishment (Figure 2.3). Each replication of the site preparation treatment is 0.0107-hectare.

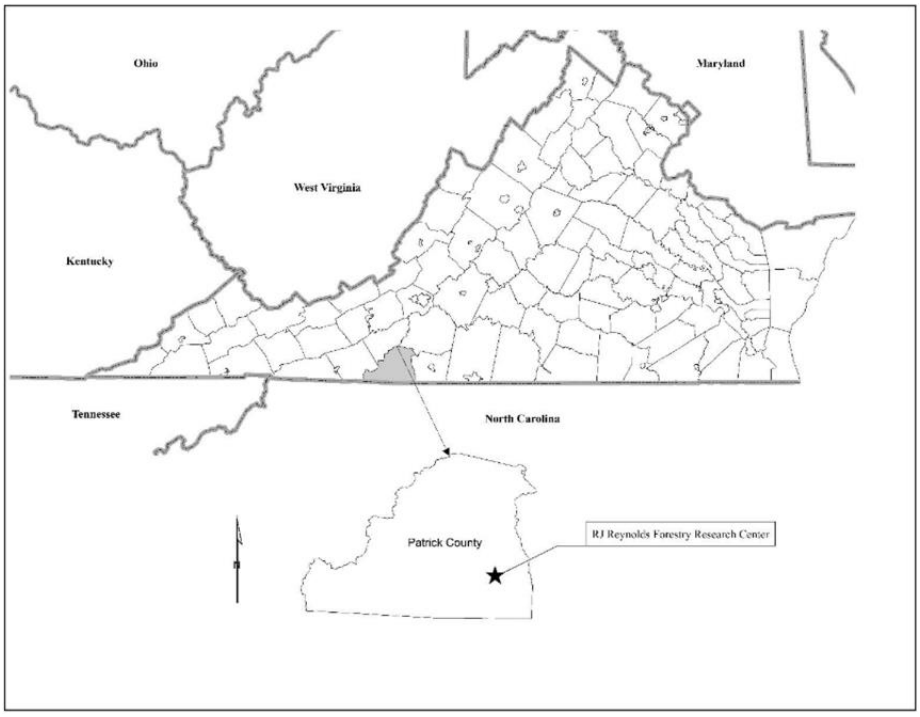

Figure 2.1:Location of Reynolds Homestead, in Critz, VA. Figure from Steele, 2020.

Figure 2.2: Aerial photos of plot locations before (2011) and after (2020) planting, showing new forest cover on all plots (Google Earth Pro).

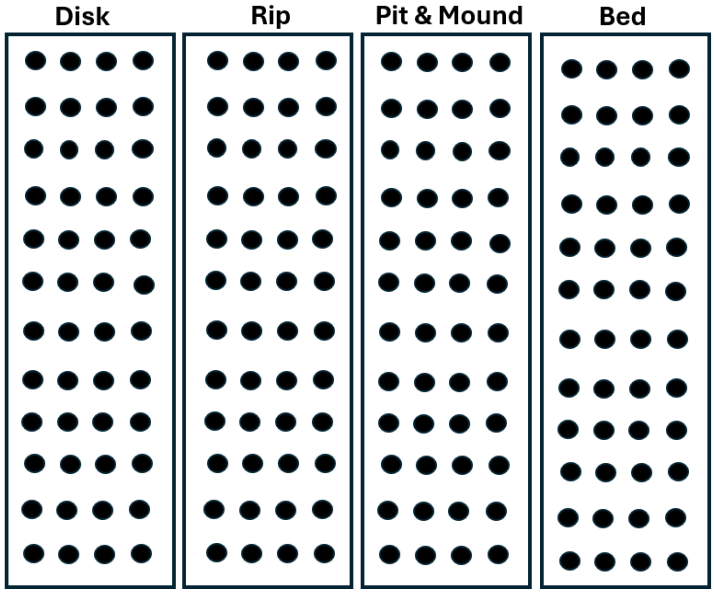

Figure 2.3: An example of an idealized block with replication of each site preparation treatments having 4 rows of 12 panted trees.

Site Preparation Treatments

Before any mechanical site preparation treatments were installed, all sites were sprayed with glyphosate herbicide to reduce the lush old field herbaceous competition. We evaluated the

four original site preparation treatments that were used to establish the plantation, which represented operational treatments that had been used in other regions (e.g., coastal plain) for establishment of different species (e.g., sweetgum (*Liquidambar styraciflua*), Nuttall oak (*Quercus nuttallii*)). The pit and mound treatments were installed with a farm tractor equipped with a backhoe to excavate the pit and create a mound (Figure 2.4). Elevated beds (bed) were established with a small bulldozer that was used to blade the soil into bed shapes. The ripping treatment (rip) was installed with a farm tractor equipped with 60 cm ripping shanks which were pulled through the soil under the planting rows. The disk treatment was installed using a farm tractor pulling a gang type disk harrow. Figure 2.4 shows the appearance of the site preparation treatments during establishment at the Reynolds Homestead.

Figure 2.4: Establishment of disk, rip, bed, and pit and mound treatments on the Reynolds Homestead riparian site (clockwise from top left). Photos from W. M. Aust.

Field Methods:

All surviving American sycamores within each site preparation treatment were evaluated. Tree diameters at breast height (DBH) were measured with a diameter tape. Tree total heights were measured using a Nikon Forestry Pro II hypsometer. Biomass values were calculated using existing equations that used total height and DBH to predict total tree dry weight including the wood and bark (Clark et. al (1986). Carbon values of American sycamore were calculated as 50% of tree dry weights (Kurz et al, 2009).

Herbaceous samples were restricted to the center two rows of each treatment plot, limiting effects from adjacent treatments. Four of the five original American sycamore blocks were sampled for herbaceous vegetation. A 30 cm^2 sampling frame was placed at randomly selected points and all herbaceous stems within the frame were clipped, collected, labeled, and placed in a cooler for transport to the lab.

The litter sample included the O_i, O_e, and O_a organic soil layers and was therefore included as a below-ground pool. Litter sampling followed a similar protocol as herbaceous sampling, with a 30 cm^2 sampling frame being used to collect litter samples on the inner two rows. Four of the five American sycamore blocks were sampled for litter.

Fine root samples were collected using a modified 6.5 cm diameter auger with saw teeth attached (McKee et al. 2013). Samples were taken within the inner 2 rows of each treatment. The auger was used to sample to 30 cm soil depth. The collected samples were washed over a 2 mm screen to separate roots from mineral soil. Four of five American sycamore blocks were sampled for fine roots.

Soil carbon masses were sampled by combining bulk density with a percent carbon measurement. A double cylinder bulk density slide hammer equipped with 5 cm long cores was used to collect three bulk density samples from to soil depths of 0-10 cm, 10-20 cm, and 20-30 cm. Bulk density samples were taken in four American sycamore blocks, with each treatment being sampled in every block. Soil carbon samples were collected using a push tube to sample 0-10 cm, 10-20 cm, and 20-30 cm, in a method similar to Ellert et al. (2001).

Lab Methods:

Herbaceous, litter, and root samples were oven-dried at 65^0C until weights stabilized. The dried samples were weighed and ground in a mill. A subsample of each ground sample was analyzed for percent carbon using a CNS Elementar Max. The mass and percent carbon were used to calculate the mass of carbon in each sample, which was converted to a mass/area in metric tons/hectare to a depth of 30 cm.

Bulk density samples were oven dried at 105^0C for at least 24 hours. Dried samples were weighed, then ground. Ground samples were washed over a screen to separate coarse fragments. The volumes and weights of the coarse fragments were used to correct the bulk density of the soil. Soil carbon samples were oven dried at 65^0C. Dried samples were ground and sifted over a screen to separate coarse fragments. The soil samples were analyzed for percent carbon using CNS Elementar Max. Bulk density and paired soil carbon percentages were multiplied to determine the mass of carbon in a fixed volume, which was converted to mass of soil carbon per hectare to 30 cm depth.

Statistical Analysis:

All carbon values were converted into Megagrams per hectare (Mg ha^{-1}) for analyses, except for survival, which was characterized by survival percent. The experimental design of the current study is a randomized complete block design with four blocks of American sycamore established following four mechanical site preparation treatments. Shapiro Wilks Goodness of Fit tests were used to examine data normality. Most parameters were not normally distributed, therefore nonparametric Kruskal-Wallace tests were used to determine if treatment differences existed and subsequent Tukey treatment separation analyses were used to detect differences between specific treatments ($\alpha \leq 0.05$).

Results:

Site preparation treatments had no significant effect on of the quantity of carbon stored within the planted American sycamore treatments and ranged from 30.0 Mg ha^{-1} in the pit and mound treatment to 16.0 Mg ha^{-1} in the disk treatment (Table 2.1) ($p<0.38$ $\alpha \leq 0.05$). Both the means and the medians followed similar trends for site preparation treatment rankings.

Table 2.1:

Comparative Statistics for Mg Ha^{-1} of Carbon Stored Within Planted Tree Strata in a 12-year-old American Sycamore Plantation as Influenced by Four Soil Treatments

p value: 0.38						
Treatments	Number of blocks	Mean (Mg ha^{-1})	Median (Mg ha^{-1})	Min (Mg ha^{-1})	Max (Mg ha^{-1})	Std Err Mean
Pit&Mound	5	30.01	27.75	11.05	57.50	7.63
Rip	5	27.51	28.60	7.93	43.14	5.79
Bed	5	21.40	23.70	5.01	34.06	4.98
Disk	5	15.97	15.36	9.78	29.32	3.56

Survival of American sycamore did not differ between site preparation treatments ranging from 58.7 % in the pit and mound to 67.9 % in the rip treatment (Table 2.2). As such we fail to reject H_0 4 and accept that mechanical site preparations do not alter the survival of American sycamore plantings at 12 years).

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Table 2.2:

Comparative Statistics for Plot Survival Percent in a 12-year Riparian American Sycamore Plantation

p value: 0.20

Treatment	# of blocks	Mean % (plot)	Median % (plot)	Minimum % (plot)	Maximum % (plot)	Std Err Mean
Rip	5	67.9%	68.8%	58.3%	77.1%	3.40
Bed	5	67.5%	68.8%	54.2%	75.0%	3.64
Disk	5	62.9%	64.6%	58.3%	66.7%	1.91
Pit&Mound	5	58.7%	58.3%	50.0%	70.8%	3.75

The Kruskal Wallis tests revealed no significant differences in herbaceous vegetation carbon response due to site preparation treatments (Table 2.3). The highest mean was in the disked plots, and the lowest was in the rip plots.

Table 2.3

Comparative Statistics for Mg ha^{-1} of Herbaceous Vegetation Carbon in a 12-year-old American Sycamore Riparian Plantation

p value: 0.57

Treatment	Number of Replications	Mean (Mg ha^{-1})	Median (Mg ha^{-1})	Min (Mg ha^{-1})	Max (Mg ha^{-1})	Std Err Mean
Disk	4	0.58	0.55	0.43	0.75	0.08
Bed	4	0.47	0.42	0.32	0.73	0.10
Pit&Mound	4	0.42	0.42	0.61	0.61	0.09
Rip	4	0.40	0.43	0.19	0.56	0.08

No significant differences (p=0.09) were revealed by Kruskal Wallis between site preparation treatments carbon storage in the litter layer (Table 2.4).

Table 2.4

Comparative Statistics for Mg of Carbon per Ha in the Litter of a 12-Year American Sycamore Plantation with Four Site Preparation Treatments

p value: 0.09

Treatment	Number of Samples	Mean (Mg ha^{-1})	Median (Mg ha^{-1})	Min (Mg ha^{-1})	Max (Mg ha^{-1})	Std Err Mean
Pit&Mound	4	4.47	4.15	3.74	5.80	0.46
Rip	4	3.26	3.67	1.47	4.19	0.62
Bed	4	3.13	3.06	2.40	4.00	0.33
Disk	4	2.71	2.52	2.32	3.49	0.26

There were no significant differences in fine root carbon between the site preparation treatments which ranged from 2.2 in the disk to 2.6 in the bed (Table 2.5).

Table 2.5

Comparative Statistics for Fine Root Carbon (Mg ha^{-1}) to a Depth of 30 cm in a 12-Year American Sycamore Plantation with Four Site Preparation Treatments

p value: 0.89

Treatment	Number of Samples	Mean (Mg ha^{-1})	Median (Mg ha^{-1})	Min (Mg ha^{-1})	Max (Mg ha^{-1})	Std Err Mean
Rip	4	2.58	2.51	1.66	3.62	0.41
Bed	4	2.60	2.36	1.99	3.68	0.39
Pit&Mound	4	2.29	2.31	1.64	2.91	0.28
Disk	4	2.19	2.21	1.01	3.35	0.49

There was no significant difference ($p \leq 0.55$) due to site preparation treatments (Table 2.6) with the disk treatment having the highest with 47.4 Mg ha^{-1} and the bed treatment the lowest with 42.6 Mg ha^{-1}.

Table 2.6

Comparative Statistics for Mg ha^{-1} of Carbon Stored in Soil Carbon to a Depth of 30 cm Across Four Site Preparation Treatments in an American Sycamore Riparian Planation

p value: 0.55

Treatment	Number of Replications	Mean (Mg ha^{-1})	Median (Mg ha^{-1})	Min (Mg ha^{-1})	Max (Mg ha^{-1})	Std Err Mean
Disk	4	47.41	47.62	39.31	55.10	3.24
Pit&Mound	4	45.67	46.00	42.77	47.93	1.08
Rip	4	44.64	44.30	40.76	49.20	2.14
Bed	4	42.61	42.86	37.67	47.03	2.07

Neither aboveground nor belowground carbon pools differed significantly. As such we fail to reject $H_0$1 and $H_0$2. There were no significant differences between site preparation treatments in total carbon (sum of all pools) (Table 2.7). We fail to reject $H_0$3. In all site preparation treatments, the highest pool of carbon storage was within the soil to 30 cm depth, which contained over 50% of the carbon storage for all treatments. Belowground carbon was higher than aboveground in all treatments. The planted American sycamore pool held the second largest quantity of carbon in all treatments, between 23 and 37% of the total carbon. The litter layers stored the third greatest carbon quantity with a mean of 4-5% of carbon stored per soil treatment. Fine roots were fourth in carbon in all treatments, with 3-4%. Herbaceous vegetation held the least carbon in all four soil treatments, below 1% in all treatments.

Table 2.7

Mean Mass and Percent of Carbon in Mg ha^{-1} by Carbon Pool and Total by Site Preparation Treatment in a 12-Year-Old American Sycamore Plantation

	Bed		Disk		Pit&Mound		Rip		p value
	Mean (Mg ha^{-1})	%	Mean (Mg ha^{-1})	%	Mean (Mg ha^{-1})	%	Mean (Mg ha^{-1})	%	
Planted	21.4	30.4%	16.0	23.3%	30.01	36.2%	27.5	35.0%	0.38
Herb	0.5	0.7%	0.6	0.8%	0.4	0.5%	0.4	0.5%	0.20
Litter	3.1	4.5%	2.7	3.9%	4.5	5.4%	3.3	4.2%	0.03
Fine Roots	2.6	3.8%	2.2	3.3%	2.3	2.9%	2.6	3.4%	0.57
Soil Carbon	42.6	60.6%	47.4	68.7%	45.7	55.0%	44.6	56.9%	0.05
Aboveground	21.9	31.1%	16.2	24.0%	30.4	36.7%	27.9	35.5%	0.38
Belowground	48.4	68.9%	52.4	76.0%	52.5	63.3%	50.6	64.5%	0.35
Total	70.3	100%	69.0	100%	83.0	100%	77.6	100%	0.35

Figure 2.5: At 12 years after planting, all four site preparation treatments (left to right: bed, disk, pit and mound, rip) provided sycamore overstory cover.

Discussion

Survival:

All four site preparation treatments successfully restored American sycamore plantations on old field riparian sites (Figure 2.5), with the lowest survival being slightly over 50% at 12 years. A riparian American sycamore planting in Northern Virginia led to survival ranging from 45-59%, which was lower than any treatment in our study (Roquemore et al, 2014). The success of all treatments in establishing a riparian forest may be due to reduction in soil compaction, which facilitated improved rooting (Gardiner et al, 2000). The riparian restoration was also aided by the suitability of American sycamore to this site (Gardiner et al, 2000, Steele et al, 2021). Large, naturally regenerated American sycamore existed along the stream both above and below the research sites and soil evaluations conducted by Steele et al. (2021) also affirmed the suitability of the species to the site.

Although previous research had detected differences due to the mounding mechanical site preparation, the results of this study indicate that site preparation treatments had no significant lasting effects on the survival of planted American sycamore at 12 years. Other studies have shown that mechanical site preparation effects can help with initial survival and growth, but that the effects may be transitory as the tree roots expand beyond the site preparation (Lang et al. 2015, Neaves et al. 2016). The pit and mound microsites were considered as one treatment in our analysis, as the formation of a soil mound was paired with a pit, making them connected treatments in terms of a replication's carbon storage. However, the combined pit and mound survival rates did not have uniform survival across each individual microsite. In the pit and mound treatment, 61% (88/143) of surviving trees were on mounds. The low overall survival for the combined pit and mound resulted from very low survival in the pits. Averaging the higher

survival on the mounds with lower survival within pits prevented the combined pits and mounds from having a statistically significant lower survival. These results correspond to research indicating that American sycamore plantings may favor raised positions, while American sycamore may decline on lower, wetter microsites (Hodges, 1997, Simmons et al, 2013). Previous research on this same study site also found minimal survival differences in the first four years between site preparation treatment when pits survivals were excluded (Steele et al, 2021). Steele analyzed pits and mounds as separate treatments for tree survival, and the pits and mounds were the only treatments found to be significantly different at four years, with the mounds having the highest survival and the pits the lowest.

Aboveground Carbon:

Site preparation treatments had no significant impact on aboveground carbon storage after 12 years, despite Steele et al (2021) showing some early growth differences on four year old stands due to site preparation. Similarly, an 11-year study showed bedding improves oak seedling survival and early growth compared to control former agriculture sites, but growth in the elevated beds equalized with control treatments over time (Self et al, 2012, Self and Willis, 2022). Reduction of plow pans is known to be beneficial to establishing fast growing species on former agricultural sites, and ripping is known to be effective at reducing these pans (Gardiner et al, 2000). While we did find ripping to be effective for establishing American sycamore, ripping was not significantly different in terms of aboveground carbon storage. Aust et al. (1995, 1998) evaluated mechanical site preparation on compacted wet mineral flats and found that disking or disking and bedding was less beneficial to survival and growth of planted pines as compared to bedding and concluded that the disking reduced the soil drainage of the wet sites. Our study did

not find disking and bedding to be significantly different in terms of aboveground carbon, suggesting that the impact of soil treatments will vary by wetland site.

Individual trees on the mound contained the most carbon of any treatment. On average, trees on the mounds were larger, and the average pit and mound areas contained 2.5 metric tons of additional carbon as compared to the rip treatments, despite the rip plantings having a 9.2% higher survival rate. Initial American sycamore measurements by Steele's group (2021) at four years also found the mound treatment to have the highest biomass and the rip treatment to have the second highest. Simmons et al. (2013) found American sycamore growth to be the highest on ridges, and lowest in hydric pits. Additionally, mounding has been shown to be effective at increasing other species' survival and growth (Simmons et al, 2013, Löf et al, 2006). However, the difference is marginal, and mounding is the most expensive treatment at approximately \$1150 ha^{-1} (Thiffault et al, 2020)

Bedding did not allow the same gains for individual tree growth as mounding. The beds were initially created to a height of ~50 cm above the groundline, while mounds were substantially higher, initially ~90 cm high (Steele et al, 2021). The benefits of higher relief in wetlands are related to having depth to root above the water table and perhaps greater initial volume of non-compacted soils, and mounding was apparently better for increasing the aerated rooting zone, thus increasing early growth (Londo and Mroz, 2001). Increased failures of trees in adjacent pits also supports the aerated root premise and probably reduced within species competition for trees on mounds, allowing for more growth. Steele et al. (2021) also found mounds to be the largest planted trees at four years, significantly larger than any other treatment. Comparing the two treatments that created microtopographic relief, pit and mounding showed more promise than bedding in storing carbon within planted American sycamore on this site.

Carbon storage masses within herbaceous vegetation were not found to differ among treatments. Due to the success and growth of the American sycamore, closed canopy conditions existed, thus limiting the herbaceous strata and consequently herbaceous plants were a small proportion of the total carbon storage (generally ≤ 1%) of the total carbon. Furthermore, herbaceous vegetation did not offset overstory carbon storage between site preparation treatments. For example, the disk treatments had 15.5 metric tons of carbon less in the planted strata than pit and mounds (about 50% less), but only averaged 0.2 metric additional tons of carbon in herbaceous vegetation.

Belowground Carbon:

Belowground carbon included the carbon within the mineral soil to 30 cm, fine roots, and litter. A more complete accounting of below-ground carbon may include large tap roots, soil microbes, and a deeper measure of soil carbon (Bansal et al, 2023), but those pools were beyond the constraints of this project. Overall, more carbon was stored belowground in litter, soil, and fine roots than aboveground in planted and herbaceous vegetation. Within the belowground pools, carbon stored in the top 30 cm of the soil comprised the majority of carbon storage. Soil carbon is the largest pool of carbon across all soil treatments and holds the majority of carbon in all treatments. These findings agree with other research showing soil is the largest wetland carbon sink (McKee et al, 2013, Temmick et al, 2022). The only significant differences in soil carbon were between the bed and the disk treatments, with the disk holding an additional 4.8 Mg ha^{-1} hectare of soil carbon. This was the largest difference between treatments, perhaps due to higher planting survival in the bed, yet these differences were minor in comparison to total carbon storage. These results also suggest that the site preparation treatments had limited effects on soil carbon 12 years after planting. This is supported by other research showing aboveground

carbon to be the largest source of variation within a wetland site (Giese et al, 2000, McKee et al, 2013) and the pool that offers the largest management opportunities. While soil carbon may not show great variance, creating and maintaining soil health is key to holding carbon in wetland restoration due to its status as the greatest carbon sink, and root turnover may affect belowground carbon pools within these treatments in the future.

Carbon storage within the litter pool was found to be significantly higher in the pit and mound treatment than within the disk or bed treatments after 12 years, and pit and mound litter layer had the greater carbon storage of any site preparation treatment. The lower and wetter position of the pit microsites appear especially effective at trapping litter and storing carbon as was also found by Ott et al. (2020), when evaluating carbon reforestation via pit and mound site preparation.

While fine root carbon masses were not found to be significantly different due to mechanical site preparation treatment means, the bed and pit and mound treatments provide a greater range than the disk and flat treatments. The greater range of the bed and pit & mound treatments may be explained by the variation of the microtopography. However, our root data were limited to fine root samples and did not include course roots, thus we are hesitant to draw definite conclusions about total root carbon storage.

Total Carbon:

The mineral soil contained the greatest quantity of belowground carbon, while the second largest carbon pool was aboveground planted American sycamore. Litter, fine roots, and herbaceous vegetation pools were of lesser importance and followed in that order. These results imply that restoration efforts including only tree reestablishment following mechanical site

preparation will have minimal effects on soil carbon storage. If more immediate soil carbon increases are desired, treatments such as those used by Daniels et al. (2005), which added compost to wetlands might be considered. While mounding increased tree growth, the pit and mounding treatment did not hold significantly more carbon. However, some researchers have attempted interplanting of hardwood species in restoration efforts, and pit and mound treatments might offer such an opportunity (Gardiner et al, 2004, Pietryzkowski et al, 2015). For example, more hydric species such as cypress (*Taxodium distichum*) or swamp tupelo (*Nyssa biflora*) could be planted in the pits while American sycamore could be planted on the mounds.

From an operational standpoint the rip treatment was effective and offers a potentially practical and less expensive treatment than pit and mounding. The rip had high overall tree survival, a high planted biomass, and 77.6 Mg ha^{-1} mean total carbon storage. Riparian restoration efforts often have the specific goal of establishing large biomasses of pioneer species in wetland plantings due to federal wetland restoration tree height requirements. Such restorations could benefit from pits and mounds, but rip treatments could also be effective. The rip treatment also is advantageous because ripping plows are commonly available, equipment operators are more available than excavator operators for pit and mounding, and because pit and mounds are more expensive to install. Referencing a 2020 study, we estimate mounding to cost $1,100/hectare and ripping to cost about $170/hectare (Barry et al (accessed online, 2024), Self and Kushla (accessed online, 2024), Thiffault et al, 2020). Overall, all the site preparation treatments resulted in well- or even over-stocked American sycamore plantations, with no significant difference in total carbon storage.

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Chapter 3: The Effects of Mechanical Site Preparation Treatments on Carbon Pools and Survival in a 12-Year-Old Piedmont Willow Oak (*Quercus phellos*) Riparian Plantation

Abstract:

Bottomland oak species are commonly planted on wetland restoration sites to establish forests that provide hard mast for wildlife in addition to water quality protection. Carbon storage is another benefit from these restorations that has gained interest. We evaluated a 12-year-old riparian restoration that was planted with willow oak (*Quercus phellos*) on four different mechanical site preparation techniques (pit and mound, bed, rip, and disk) to determine if the different mechanical site preparation treatments affected carbon storage across multiple pools. The planted oak overstory, herbaceous layer, litter, roots, and soil carbon masses were evaluated. Across all treatments, soil contained over 2/3rds of the carbon, with trees containing the next largest carbon pool. While pit and mounds increased planted oak carbon by increasing growth, no mechanical site preparation treatment was found to significantly affect the survival of planted oaks, or the total carbon stored across all pools. Our results indicate that all mechanical site preparation techniques established well-stocked willow oak plantations, but this can probably be attributed to the original high planting density rather than benefits from any specific mechanical site preparation method.

Introduction:

Forested wetland ecosystems provide multiple ecosystem services, helping to protect water quality, providing food and fibers, sequestering carbon, and providing wildlife habitat (Stelk and Christie, 2014). These wetlands have historically been drained and converted for agriculture and development. It is estimated that 50% of global wetland area has been lost since 1700 (Davidson, 2014). In 1987, wetlands became included under the Federal Water Pollution Control Act of 1972 (Clean Water Act) (Deland, 1992), making the unpermitted disturbance of a wetland illegal under federal law in the United States, except for certain silvicultural and agricultural operations. Permits to disturb a wetland often require the creation or restoration of a similar wetland of equal of greater area, supporting the concept of “No Net Loss of Wetlands” as attributed to President Bush. The federal and state wetland programs and permit requirements also may require the planting of hard mast producing species (e.g., oaks) and the uncertainty of oak regeneration has generated increased interest in techniques that can increase the oak component in wetland restorations.

Riparian forest wetlands are found on alluvial floodplains of rivers and streams. Riparian areas that were previously converted to agriculture have been a focus of restoration efforts, as their streamside position gives them a disproportional influence on water quality (Gardiner et al, 2004), which would be enhanced by restoration. Riparian areas can be highly productive due to saturated soils and alluvial deposits (Hodges, 1997). Varied flood disturbance, fluctuating water tables, and access to drinking water make riparian wetlands a highly diverse ecosystem for both flora and fauna (Naiman and Decamps, 1997). In recent decades, riparian forest restoration has received funding from a variety of government initiatives, such as the Wetland Reserve Program and the Conservation Reserve Enhancement Program (Bradburn et al, 2010, Stanturf et al 2001).

In recent years, wetlands, including forested wetlands, have been additionally recognized for their potential to accumulate and sequester carbon. Planted riparian restorations have been shown to accumulate carbon at twice the rate of non-forested riparian areas (Dybala et al, 2018), indicating that carbon storage is potentially an additional benefit of riparian restorations. Carbon accumulation in wetlands is due to a combination of high productivity of vegetation established on fertile alluvial wetlands and the saturated nature of wetland soils (McKee et al, 2013). When saturation creates the absence of oxygen, decomposition happens very slowly (Davidson & Janssens 2006). Slowed decomposition leads to a higher rate of accumulation of organic matter than dry soils (Krauss et al. 2021).

Restored and created forested wetlands provide valuable ecosystem services, however successful wetland restoration projects are not assured. Initial attempts to afforest the Lower Mississippi Valley's riparian areas saw a 90% failure of plantings to reach a standard of 247 trees per hectare (Stanturf et al, 2001). Common failures of previous wetland restoration attempts led to the development of a required 2:1 or 3:1 ratio for wetland restoration, meaning that permitting

requires double or triple as much area of forested wetland restoration or creation to offset disturbance (Brown & Lant, 1999). Failures in establishing forests on restoration sites are attributed to failures in planted tree survival, due to multiple causes. Causes include incorrect selection of species for the site characteristics, poor planting techniques or conditions, intense competing herbaceous species that can overtop planted trees, compacted soil that inhibit root growth, and lack of microtopography associated with natural wetlands (Bailey et al, 2007).

Habitat restoration is a common goal of riparian restoration, and often influences selection of planted trees. Willow oak (*Quercus phellos*), is a bottomland oak species that favors alluvial soils (Schlaegel, 1990), making it suitable for riparian wetland plantings. Willow oak also provides hard mast through acorn production, providing food for wildlife, including various mammals, waterfowl, and other birds (Cypert and Webster, 1948). Oaks are high value timber species, and oak plantations have potential to produce wood and fiber materials (Ouchley et al., 2000). Preference for alluvial sites, wildlife value, and potential for timber production make willow oak a strong candidate species for riparian planting, if site conditions are appropriate.

Willow oak, as with many other oaks, typically develops an extensive root system rather than rapid aboveground growth (Dey et al. 2008). The preference for early belowground growth causes them to initially have slower above ground growth placing willow oak as a slow to moderate growth, mid-successional tree. Willow oaks are site sensitive and are not evenly distributed across floodplains, favoring ridges and flats rather than sloughs and depressions (Hodges, 1997). Created wetlands often lack the variance of microtopography present in less disturbed floodplains, including the higher points favored by willow oak. This lack of microtopographic variance may factor into failed plantings (Bailey et al. 2007).

A variety of methods can be used to create microtopography in planted wetlands. Bedding is a mechanical site preparation treatment that uses a specialized plow to create long, linear raised beds (Miwa et al, 2004). These beds mound soil, allowing species to be planted in an artificially raised microtopographic position. Bedding is common in industrial forestry operations for establishment of pine plantations but is less common in hardwood restoration (Self et al, 2012). Pitting and mounding is a specialized mechanical site preparation treatment that uses an excavator or similar equipment to create paired pits and soil mounds (Löf et al, 2012). Pitting and mounding artificially replicates tree tip-ups that happen frequently in weaker, saturated wetland soils (Londo and Mroz, 2001). It is common for trees to naturally regenerate on the tip-up mounds, as the raised position increases the aerated rooting zone (Simmons et al, 2012). The root pits depressions are closer to the water table, thus having lower soil aeration. Pits may accumulate more litter, as debris can wash down into the pits, pits are sheltered from the wind, and their proximity to the water table creates more anaerobic conditions, slowing the decay of organic matter (Ott et al, 2020). Riparian willow oak plantings have shown increased survival and growth on mounds, and decreased survival and growth in pits (Steele, 2020).

In addition to techniques used to create microtopography, mechanical site preparation treatments can be used to offset compaction in riparian restoration projects. Traditional site preparation methods, such as ripping or disking, are meant to reduce soil compaction by plowing. Ripping effects soil at greater soils depths than disking and is sometimes called sub-soiling (Barry et al). Ripping is known to be effective at breaking up agricultural plow pans, increasing drainage and rooting potential (Gardiner et al, 2001, Löf et al, 2012). While disking and ripping treatments can reduce surface or subsurface compaction, respectively, they have little influence on microtopography (Löf et al, 2012).

Justification and Objectives:

Riparian restoration efforts often occur on previously forested sites that were converted to agriculture, which has compacted the soils and eliminated microtopography. Mechanical site preparation treatments can be effective at increasing survival and early growth in riparian plantings by reducing compaction and/or creating microtopography (Self et al, 2012, Steele, 2020)). While mechanical site preparation treatments are known to benefit plantings on former agricultural sites and show promise for increasing bottomland oak survival and growth, little research has been done to examine different effects between treatments (Self et al, 2012). Our research attempts to measure the effects of mechanical site preparation treatments, including those intended to create microtopographic variation. This research will quantify treatment impact on willow oak survival and impact on carbon storage across several different carbon pools. Willow oak is an appropriate candidate for riparian plantings on alluvial sites in Virginia, particularly for riparian restorations that are intended to favor wildlife that require hard mast. Related studies are often focused on early growth of trees, not long-term effects or measuring carbon beyond planted biomass (Steele et al, 2021, Simmons et al, 2012, Gardiner et al, 2004). This research will utilize 12-year-old willow oak riparian plantations in the Virginia Piedmont to measure planting survival and five carbon pools (planted oaks, herbaceous layer, litter, roots, mineral soil) across mechanical site preparation treatments. The planted oaks were installed in a block design across a riparian planting that was established to quantify the survival and early growth impacts of mechanical site preparation treatments (Steele dissertation, Curtis et al, 2015). This current research evaluated the site and vegetation, to determine the impacts of mechanical site preparation treatments at 12 years on above- and below-ground carbon storage. This goal

will be accomplished via the following objectives and testing of the associated null hypotheses as outlined below.

Objective 1. Determine if mechanical site preparation treatments impact the aboveground carbon stored in willow oak plantings. This includes planted trees herbaceous vegetation.

1) H0: Mechanical site preparation treatments do not alter aboveground carbon for willow oak plantings.

Objective 2. Determine if mechanical site preparation treatments impact belowground carbon stored in riparian plantings of willow oak. This includes leaf litter, fine roots, and soil carbon.

2) H0: Mechanical site preparation treatments do not alter belowground carbon for willow oak.

Objective 3. Determine the effects of mechanical site preparation treatments on total carbon stored across all measured carbon pools.

3) H0: Mechanical site preparation treatments will not impact total carbon storage.

Objective 4. Measure the survival of planted willow oak across four mechanical site preparation in a riparian restoration.

4) H0: Mechanical site preparation treatments do not alter the survival of willow oak plantings at 12 years.

Methods

Study Site:

The riparian restoration study site is located at the Virginia Tech Reynolds Homestead Forest Resources Research Center. The Reynolds Homestead is a 280-hectare area in the Piedmont region of Patrick County, Virginia (Figure 3.1). In the 1800s, the forests were

converted to tobacco plantations in the uplands, and corn or similar crops in the bottomlands (Steele et al, 2021). The riparian zone of the site is located on the eastern floodplain of an unnamed, first order tributary that enters Mill Creek. The watershed of the stream is 512 ha according to USGS stream stats. The site soils are mapped as 79.4% French loam, 20.2% Braddock fine sandy loam, and 0.4% Fairview sandy soils (Web Soil Survey, 2023). The floodplain is active, with 25 cm of flooding occurring most spring seasons (Curtis et al, 2015), and managers reporting 1-2 floods in normal years (Steele et al, 2021). Past disturbances include agriculture and more recently forestry soil compaction experiments. The riparian restoration study was planted in May 2011 to determine survival and growth of American sycamore (*Platanus occidentalis*) and willow oak using various planting stock sources, planting aids, and soil mechanical site preparation treatments. The planting aid and planting stock treatments were replicated randomly and had equal distribution across the mechanical site preparation treatments. Only the impacts of mechanical site preparation treatments will be considered in our study. The study area is now comprised of small hardwood plantations with a variety of created microtopography (Figure 3.2). Four of the original five willow oak blocks were sampled in our study. Each block is 0.0429 hectares. The four blocks each had the following mechanical site treatments applied: bedding, disking, pit and mounding, and ripping. Each block contains one complete replication of each mechanical site preparation treatment. A treatment replication initially contained four rows of 12 planted trees, planted at a density of 4 ft (1.22 m) * 6 ft (1.83 m), making this a densely stocked plantation (est. ~4,500 seedlings/Ha). Each replication of the soil treatment is 0.0107-hectare.

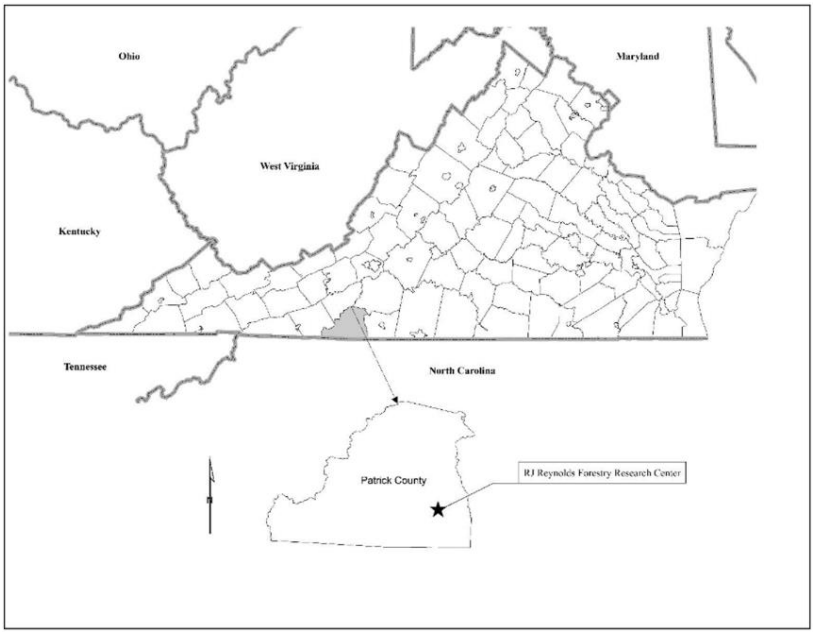

Figure 3.1:Location of Reynolds Homestead, in Critz, VA. Figure from Steele, 2020.

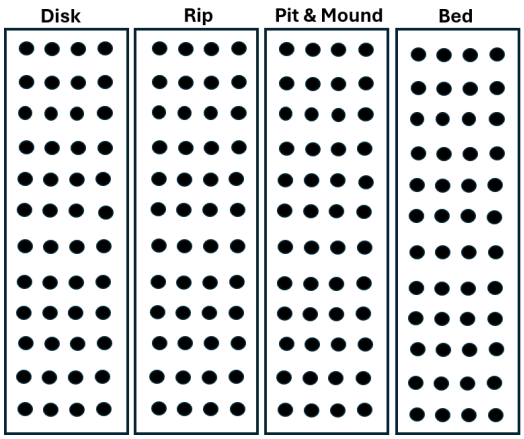

Figure 3.2: An example block, showing one possible random arrangement of mechanical site preparation treatments.

Figure 3.3: Aerial photos of plot locations before (2011, left) and after (2020, right) planting, showing new forest cover on all plots (Google Earth Pro).

Treatments

All sites were sprayed with glyphosate herbicide to reduce the lush herbaceous competition prior to mechanical site preparation. The four mechanical site preparation treatments used to establish the willow oak represent treatments have been used in other regions (e.g., coastal plain) for establishment of a variety of species (e.g., nuttall oak (*Quercus nuttallii*), and sweetgum (*Liquidambar styraciflua*). Pit and mound treatments were installed with a farm tractor equipped with a backhoe to excavate the pit and create an adjacent mound. Elevated beds (bed) were established with a small bulldozer that was used to blade the soil into bed shapes. The ripping treatment (rip) was installed with a farm tractor equipped with 60 cm ripping shanks which were pulled through the soil under future planting rows. The disk treatment was installed with a farm tractor pulling a gang disk harrow (Curtis et al, 2015). Figure (3.4) shows the application of treatments at the Reynolds Homestead site.

Figure 3.4: Establishment of disk, rip, bed, and pit and mound treatments on the Reynolds Homestead Riparian site (clockwise from top left). Photos from W. M. Aust.

Field Methods:

All surviving willow oaks were measured in each mechanical site preparation treatment in the four willow oak blocks. Tree diameter at breast heights (DBH) were measured with a Spencer diameter tape. Tree heights were measured using a Nikon Forestry Pro II Hypsometer. Biomass values were predicted using existing equations for total tree dry weight in the wood and bark from Clark et. al (1985) that use total height and DBH. Carbon was assumed to equal 50% of estimated dry biomass. Equations for Water oak (*Quercus nigra*) were used as suitable equations for willow oak did not include both diameter and height and water oak is a similar species.

Herbaceous sampling was restricted to the center two rows of each treatment replication, limiting interference from adjacent treatments. Four oak blocks were sampled for herbaceous vegetation. A 30 cm^2 sampling frame was placed at randomly selected points and all herbaceous vegetation within the frame was clipped, collected, labeled, and placed in a cooler for transport.

Litter sampling followed a similar protocol as herbaceous sampling, with a 30 cm^2 sampling frame being used to collect litter samples on the inner two rows. Four oak blocks were sampled for litter. The litter layer included the O_i ,O_e, and O_a organic soil horizons.

Root samples were collected using a modified 6.5 cm diameter auger with saw teeth attached (McKee et al. 2013). Samples were taken along the inner two rows of each treatment. The auger was used to sample down to 30 cm depth. The collected samples were washed over a two mm screen to separate roots from mineral soil. Four oak blocks were sampled.

Soil carbon mass was calculated by combining bulk density with a percent carbon measurement. A double cylinder bulk density slide hammer was used to collect bulk density samples to depths of 0-10, 10-20, and 20-30 cm. Bulk density samples were taken in four willow oak blocks, with each treatment being sampled in every block. Soil carbon samples were collected using a push tube to sample at 0-10, 10-20, and 20-30 cm depths (Ellert et al. 2001). Samples were collected from within the A_p, B_w and B_t soil horizons.

Lab Methods:

Herbaceous, litter, and root samples were dried at 65^0C until a stable weight. The dried samples were weighed. The weighed samples were ground in a mill. A part of each ground sample was analyzed for percent carbon using a CNS Elementar Max. The mass and percent carbon were used to calculate the mass of carbon in each sample.

Bulk density samples were oven-dried at 105^0C to a stable weight. The dry samples were weighed and then ground. The ground samples were washed over a screen to separate the coarse fragments. The volume and weight of the coarse fragments were used to correct the bulk density of the mineral soil.

Soil carbon samples were dried at 65^0C. Dried samples were ground and sifted over a screen to separate coarse fragments. The soil samples were kept dry and analyzed for percent carbon using CNS Elementar Max. Bulk density measurements were multiplied by soil carbon percentages of matching locations to determine the mass of carbon in a fixed volume.

Statistical Analysis:

All parameters, except survival percentage, were converted into Mg ha^{-1} for analyses. The portion of the original experiment used in the current study is a randomized complete block design with four blocks of each species and four soil mechanical site preparation treatments. Shapiro Wilks Goodness of Fit tests were used to examine data normality. Because most pools were not normally distributed, nonparametric Kruskal-Wallis tests were used to determine if treatment differences occurred, followed by a subsequent Tukey separation analysis if differences were detected.

Results

The willow oak planted carbon pool did not differ significantly ($p=0.46$, $\alpha=0.05$) between the mechanical site preparation treatments (Table 3.1), ranging from a high of 15.2 in the pit and mound treatment to 10.7 Mg ha-1in the rip treatment. All treatments were successful in establishing willow oak (Figure 3.5).

Table 3.1

Comparative Statistics for Carbon (Mg ha^{-1}) Stored in Planted 12-year-old Willow Oak Plantation Established with Four Mechanical Site Preparation Treatments

p value: 0.46

Treatment*	# of Plots	Plot Mean (Mg ha^{-1})	Plot Median (Mg ha^{-1})	Plot Min (Mg ha^{-1})	Plot Max (Mg ha^{-1})	Std Error
Pit & Mound	4	15.2	16.8	9.0	18.2	2.13
Disk	4	9.9	9.9	3.4	16.4	3.44
Bed	4	11.3	10.7	7.0	16.9	2.06
Rip	4	10.7	8.7	6.2	19.3	2.96

Figure 3.5: The four mechanical site preparation treatments (left to right: bed, disk, pit & mound, rip) used for the willow oak forest restoration after 12 growing seasons.

Analysis revealed no significant difference ($p \leq 0.42$) for planted tree survival percentages based on mechanical site preparation treatments (Table 3.2). As such, we fail to reject $H_0 4$.

Table 3.2

Comparative Statistics of Four Mechanical Site Preparation Treatments on Survival Percent in a 12-year Riparian Willow Oak Plantation

p value: 0.42

Treatment	# of Plots	Mean	Median	Min	Max	Std Err Mean
Bed	4	48.4%	51.0%	33.3%	58.3%	5.7
Rip	4	43.8%	43.8%	39.6%	47.9%	1.9
P&M	4	39.1%	35.4%	29.2%	56.3%	6.0
Disk	4	38.5%	32.3%	22.9%	66.7%	9.6

Herbaceous carbon did not differ significantly ($p \leq 0.74$) due to mechanical site preparation treatments (Table 3.3). The pit & mound and bed treatments held the least herbaceous carbon.

Table 3.3

Comparative Statistics of the Effects of Mechanical Site Preparation Treatments on Carbon Storage (Mg ha^{-1}) within Herbaceous Vegetation in a 12-year-old Willow Oak Riparian Plantation

p value: 0.74

Treatment	Number Replications	Mean (Mg ha^{-1})	Median (Mg ha^{-1})	Min (Mg ha^{-1})	Max (Mg ha^{-1})	Std Err Mean
Disk	4	1.59	0.62	0.27	4.86	1.09
Rip	4	0.63	0.33	0.27	1.57	0.32
P&M	4	0.44	0.41	0.27	0.67	0.10
Bed	4	0.42	0.42	0.20	0.65	0.12

No significant differences($p \leq 0.36$) of carbon storage were found within the litter layer across the four soil treatments (Table 3.4).

Table 3.4

Comparative Statistics for Carbon (Mg ha^{-1}) Stored in the Litter of a 12-Year Willow Oak Plantation as Influenced by Four Mechanical Site Preparation Treatments

p value: 0.36

Treatment	Number Replications	Mean (Mg ha^{-1})	Median (Mg ha^{-1})	Min (Mg ha^{-1})	Max (Mg ha^{-1})	Std Err Mean
Pit&Mound	4	3.12	3.03	1.64	4.78	0.64
Rip	4	2.39	2.32	1.99	2.92	0.22
Bed	4	2.31	2.19	1.25	3.64	0.52
Disk	4	1.90	1.90	0.99	2.79	0.44

Carbon storage within fine roots was not significantly different ($p \leq 0.20$) across the four mechanical site preparation treatments (Table 3.5).

Table 3.5

Comparative Statistics for Carbon Stored (Mg ha^{-1}) within the Fine Roots to a Depth of 30 cm in a 12-Year Willow Oak Plantation with Four Mechanical Site Preparation Treatments

p value: 0.20

Treatment	Number Replications	Mean (Mg ha^{-1})	Median (Mg ha^{-1})	Min (Mg ha^{-1})	Max (Mg ha^{-1})	Std Err Mean
Disk	4	2.43	2.47	2.09	2.68	0.13
Bed	4	1.70	1.66	1.02	2.45	0.34
Rip	4	1.44	1.20	0.63	2.72	0.45
Pit & Mound	4	1.26	1.42	0.52	1.69	0.26

Mechanical site preparation treatments did not significantly influence soil carbon storage within the upper 30 cm of soil ($p \leq 0.95$) across soil treatments (Table 3.6). treatment.

Table 3.6

Comparative Statistics for Soil Carbon Storage (Mg ha^{-1}) in Soil Carbon to a Depth of 30 cm Across Four Mechanical Site Preparation Treatments in a 12 year old Willow Oak Riparian Plantation

p value: 0.95

Treatment	Number Replications	Mean (Mg ha^{-1})	Median (Mg ha^{-1})	Min (Mg ha^{-1})	Max (Mg ha^{-1})	Std Err Mean
Disk	4	47.12	46.39	40.02	55.65	4.08
P&M	4	46.06	45.98	43.01	49.26	1.71
Bed	4	45.66	47.30	33.59	54.43	4.44
Rip	4	45.35	45.22	38.10	52.84	3.90

Neither aboveground nor belowground carbon pools differed significantly. As such we fail to reject $H_0$1 and $H_0$2. There were no significant differences between site preparation treatments in total carbon (sum of all pools) (Table 3.7). We fail to reject $H_0$3. Mean total carbon storage (sum of all above and belowground pools) as influenced by each mechanical site preparation treatments ranged between 60.4 Mg ha^{-1} for the rip treatments to 66.8 Mg ha^{-1} on the pit and mound treatment. Soil storage provided the largest carbon pool across all four treatments, holding between 69-75% of total carbon storage in each treatment. The planted trees were the next largest pool and contained 17-23% of carbon across treatments. In the bed, pit and mound, and rip treatments, litter held the third most carbon and fine roots held the fourth most carbon. Within the disk treatment, the third most carbon stored in fine roots and the fourth most carbon in litter. Herbaceous vegetation held the least measured carbon in all four treatments, only averaging slightly over one percent in the disk treatment.

Table 3.7

Total Carbon Storage (Mg ha^{-1}) by Carbon Pool and Mechanical Site Preparation Treatment in a 12-Year-Old Willow Oak Plantation.

	Bed		Disk		Pit & Mound		Rip		p value
	Mean	%	Mean	%	Mean	%	Mean	%	(α=0.05)
Planted	11.3	18.4%	9.9	15.7%	15.2	23.0%	10.7	17.7%	0.46
Herb	0.4	0.7%	1.6	2.5%	0.4	0.7%	0.6	1.0%	0.14
Litter	2.3	3.8%	1.9	3.0%	3.1	4.7%	2.4	3.9%	0.69
Soil C	45.7	74.3%	47.1	74.7%	46.1	69.6%	45.3	74.9%	0.94
Fine Root	1.8	2.9%	2.5	4.0%	1.3	2.0%	1.5	2.5%	0.17
Aboveground (Planted, Herb)	11.7	19.1%	11.5	18.2%	15.6	23.6%	11.3	18.7%	0.53
Belowground (Litter, SC, Fine Root)	49.7	80.9%	51.6	81.8%	50.5	76.4%	49.2	81.3%	0.90
Total	61.4	100.0%	63.0	100%	66.1	100%	60.4	100%	0.46

Discussion

Survival:

Willow oak survival was not uniform. The pit and mound had a plot minimum of 29% survival, the disk had a minimum of 23% survival. However, the low survival rates were mitigated by the high planting density (initial stock was 4,481 trees per hectare) which allowed all plots to develop an oak dominated canopy cover. However, no mechanical site preparation treatment had a mean survival rate of over 50%, and only the bed had a median survival of over 50%. No rip treatment plot achieved over 50% survival. Probably due to the high original planting density, the riparian restoration with willow oak was generally successful, but no mechanical site preparation treatment had any distinct survival advantage at 12 years.

Willow oak is known to prefer ridges and flats over sloughs and depressions in natural riparian areas (Hodges, 1997). The preferences of willow oak were generally reflected within the

treatment rankings of our pit and mound and bed treatments. The survival was not consistent within the pit and mound treatment, but it is important to recall that this treatment includes two distinctly different microsites (Figure 3.6). Eighty percent of surviving willow oaks in the pit and mound were on mounds, in elevated microtopographic positions. Research supports that elevated soil treatments lead to increased survival for planted oak on beds and mounds. Löf et al. (2006) found a mounding technique to be effective at increasing *Quercus robur* seedling survival and growth, especially when combined with herbicide treatments on herbaceous competition. Simmons et al. (2012) found late successional species such as willow oak to survive best on artificial ridges, mimicking levees and ridges of natural floodplains. Simmons group found Water oak (*Q. nigra*) to survive best on elevated ridges, with a survival of 8% in the pit and mound, and only 24% on flats (2012). Self et al (2012) found very high oak survival (94%) on several mechanical site preparation treatments at 2 years post planting, which Self attributes this largely to good site conditions and highly monitored plantings. Steele's research found that on our site, willow oak survived significantly more on mounds and significantly less in pits but found no other significant differences between treatment survival after four years (Steele, 2020).

Figure 3.6: Willow oak survival clearly increased on elevated mounds compared to hydric pits.

Aboveground Carbon:

There was no significant difference in storage of aboveground carbon (trees, herbaceous strata combined) across mechanical site preparation treatments in the willow oak plantation. Due to the extremes of microsites provided, the pit and mound had the lowest survival. In terms of carbon storage, low survival in the pits was mitigated by higher survival and growth on the mounds. An 11-year study showed bedding improves oak seedling survival and early growth compared to control former agriculture sites, but growth effects were found to equilibrate in the bed over time (Self et al, 2012, Self and Willis, 2022). As stands mature, the original early increases in individual tree growth from site preparation dissipate as the trees begin to exploit areas outside of the original mechanical site preparation treatments (i.e. roots growing outside of beds).

Survival rates in plantations have often been found to be critical to the stand accumulation of mass (Neaves et al., 2017). In the Reynolds Homestead restoration, the high planting density offered another mechanism of offsetting low survival rates and generally achieving a successful willow oak plantation.

There was no significant difference found in herbaceous carbon. The disk had a larger mean value, but the median value was closer to other treatments. The disk treatment mean was probably skewed by one disk treatment area with low planting survival, which resulted in more abundant herbaceous vegetation. While the highest herbaceous carbon storage measured on this plot was 9.01 Mg $ha^{-1}$of carbon, the median disk treatment held 9.9 Mg ha^{-1} in the planted strata and the maximum disk treatment held 16.4 Mg ha^{-1}planted willow oak metric tons, indicating that successful forest restoration has more potential to store aboveground carbon than herbaceous vegetation.

Belowground Carbon:

The mean belowground carbon pool was greater than the aboveground carbon pool within all four mechanical site preparation treatments in the willow oak plantation. Within all treatments, soil carbon to 30 cm depth was the single largest pool of carbon, forming the majority of carbon measured in all four treatments. Some research has found that lower, more hydric pits accumulate more soil carbon than other treatments (Ott et al, 2020), but our study found no significant difference at 12 years. Soil has consistently been the largest measured wetland carbon sink (Giese et al, 2000, McKee et al, 2013), so preserving healthy soils is key to any wetland being managed for carbon storage. If gaining additional soil carbon is a goal, perhaps treatments that add organic materials directly, such as a yard waste addition experiments conducted by Daniels et al. (2005) could be considered. Also, as this stand matures, additional soil carbon may be gained by root turnover and site preparation might have some long-term consequences that are not apparent at present.

Fine roots to 30 cm depth were not found to differ significantly between mechanical site preparation treatments. The pits had several very low fine root masses, including a sample with no roots found, further supporting the idea that willow oak does not prefer the lowest topography within wetlands. The sample was limited to only fine roots. This means that large tap roots were not measured, and any roots more than 30 cm below the surface were not measured, limiting the conclusions we can draw about total root carbon.

Total Carbon & Willow Oak:

Across all pools, the mineral soil contained the greatest percentage of measured carbon. The largest variation of carbon storage caused by mechanical site preparation was within carbon

stored in the planted willow oak. McKee et al. (2013) also found that aboveground biomass carbon storage was more varied than belowground values across a disturbance regime in a forested wetland, showing that successful establishment of trees may be the most impactful way to capture new carbon on a site.

Pits and mounds stored only 3.1 Mg ha^{-1} of additional carbon as compared to disking. Based on the literature, pit and mounding cost approximately $1,100/hectare in 2020 (Thiffault et al, 2020). Disking for forestry operations is less expensive, costing approximately$50-180 per hectare, depending on site and treatment specifics (Self and Kushla, (accessed online 2024)). Since no soil preparation offered a clear benefit for total carbon storage, the choice of mechanical site preparation could be based on establishment costs and equipment availability. Planting at a high density apparently offered more benefits for forest establishment of willow oak than any mechanical site preparation treatment. Our planting densities were approximately 4.2x to >10x higher than those used in either traditional forest planting or restoration recommendations, but these high densities have resulted in a stocked oak plantation that will protect water quality, provide mast production for wildlife, and store carbon. While planting density was not a tested variable in this experiment, future research could examine long term effects of planting density on tree growth and establishment in restored forested wetlands.

If carbon storage is the main goal, a faster growing species might be a better alternative than willow oak. Our research indicates that slow growing oaks may not be the most desirable species choice for plantings with the goals of densely reforesting an area or quickly accumulating planted biomass, and willow oak plantings should be limited to well suited sites. When compared to a similar study of American sycamore, willow oak had lower survival and carbon storage across all four site preparation treatments as compared to the faster growing, pioneer American

sycamores (See Chapter 4). Other studies have also found faster growing, earlier successional species such as sweetgum or cottonwoods to have higher survival and early growth than oaks (Stanturf et al, 2009, Simmons et al, 2012). Inter-plantings of mixed species have been used in some studies, and show potential for reforesting a site quickly, while allowing a desired but slower growing species to establish in the midstory (Gardiner et al, 2004, Stanturf et al, 2009). One study allowed a pioneer overstory to develop for three years and then interplanted an oak understory. The study showed promise for both establishing forest cover quickly and having established oak surviving and growing in the understory (Gardiner et al, 2004, Stanturf et al, 2009).

Bottomland oak plantings are often conducted in order to increase wildlife value by increasing available hard mast (Ouchley et al, 2000). If plantings are occurring for wildlife benefits, then treatments such as we evaluated could achieve those benefits. In this case, while the pit and mound may not have significantly increased the survival or total carbon storage of willow oak, it did increase the growth of surviving stems. Acorn production has been found to increase with individual tree DBH, not with increased stand DBH (Rose et al, 2011). Trees on mounds are larger, potentially increasing mast production and providing wildlife benefit. However, a high original planting density was possibly an influential factor that allowed adequate stocking of these willow oak stands.

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Chapter 4: Survival and Carbon Storage of American Sycamore (*Platanus occidentalis*) versus Willow Oak (*Quercus phellos*) for Riparian Restorations

Abstract:

Carbon storage is increasingly valued in forests and riparian forests have been found to sequester large amounts of carbon. Riparian forest restoration is increasingly common, yet little research exists that documents carbon stored by riparian restorations having different riparian species and silvicultural activities. Both American sycamore and willow oak are native to floodplains and both species are used in riparian restorations. American sycamore is a faster growing pioneer species, while willow oak is a slower growing mid-successional, mast producing species particularly valued for wildlife benefits. This research quantifies and compares the effectiveness of both species at establishing riparian forest and sequestering carbon across multiple above- and below-ground pools in an experimental 12-year-old bottomland plantation. For both species, soil carbon is the largest carbon pool and does not vary between species. Likewise, for both species, overstory carbon is the second greatest pool. Sycamore was better suited to the site and stored more aboveground carbon than willow oak due to better survival combined with faster growth. Our results indicate that planting well suited species at sufficiently high densities are important factors in riparian restoration and forest carbon storage.

Introduction:

Riparian forests are known to have a disproportionately large impact on stream water quality, wildlife habitat, and carbon storage (Bradburn et al, 2010, Dybala et al, 2019). To increase these benefits, riparian areas that were previously converted to agricultural use are being afforested, and government assisted programs designed to incentivize riparian forest cover have been created (Bradburn et al, 2010). Unfortunately, previous riparian restorations have experienced high failure rates due to adverse site conditions that contribute to high tree mortality (Gardiner et al, 2000). Reasons for planting failures are numerous and include poor suitability of planted species to sites, residual compaction from agricultural land use, inadequate numbers of planted trees, competition from other plants, predation, and inadequate microtopography (Steele, 2020).

Curtis et al (2015) established an experimental riparian restoration using American sycamore and willow oak plantations in the Piedmont of Southern Virginia. The plantations were originally intended to address the impacts of site preparation treatments and species selection on seedling establishment and early growth through four years. The treatment areas were prepared with four mechanical soil treatments (bedding, disking, ripping, and pit and mounding), and planted with two species. One species was American sycamore (*Platanus occidentalis*), an early successional, fast-growing riparian pioneer species. American sycamore is commonly planted on riparian restoration site to achieve early forest canopy heights (Steele, 2021). The second was willow oak (*Quercus phellos*), a mid-successional, slower growing, mid-successional riparian species. Oaks are often planted on riparian sites for production of mast for wildlife (Ouchley et al, 2000).

Our current research was conducted 12 years after treatments were established by Curtis et al. (2015) and reevaluated by Steele (2020) at 1-4 years post planting. The objective at 12 years was to evaluate the longer-term carbon storage as influenced by planting survival and growth. Main objectives were expanded to measure total carbon being stored in above- and below- ground pools for both species across site preparation treatments. Chapter 2 reported and discussed impacts of site preparation treatments specifically on American sycamore survival and carbon pools, while Chapter 3 discusses impacts specific to willow oak. This chapter will compare the effects of species and provide conclusions about improving riparian forest establishment and carbon storage using species selection and site preparation.

Survival:

Long-term survival rates of planted trees were not significantly improved by any mechanical site preparation treatments in either American sycamore or willow oak restorations.

Of the two species, American sycamore clearly had better survival than the willow oak (64%, 42%). The early successional American sycamore was well suited to the site as indicated by the on-site species and an evaluation of the soil-site factors related to site index (Baker and Broadfoot 1979) (Steele, 2020), and was able to become established and compete better with herbaceous competition and vines (Figure 4.1), whereas the mid succession willow oak follows the slower aboveground growth pattern of many oaks. Although willow oak did not survive as well as American sycamore, willow oak cover was successfully established, probably due to the high initial planting density (≈4500 ha^{-1}), which is fourfold what is commonly used for standard silvicultural plantings. A higher than recommended planting density may be a valuable management technique for slow growing oak species on compacted sites having significant competition. This may be particularly true for restoration sites often have larger budgets for establishment costs relative to commercial plantations. This may also be particularly beneficial if a desired species has limited suitability to a site (Gardiner et al, 2000), particularly with regard to the low densities often recommended (≈ 250 ha^{-1}). Furthermore, the expense of planting additional bare root seedlings is less expensive than mechanical site preparation costs.

Figure 4.1: An American sycamore plot (left) and willow oak plot (right). The American sycamore grew larger and have less competition from other vegetation (shrubs and vines) than the oak, but both species established a riparian forest.

Aboveground Carbon:

As anticipated, establishment of willow oak and American sycamore plantations clearly influenced the aboveground carbon storage (Table 4.1). For both species the planted trees contributed the largest percentage of the aboveground carbon pool, but the American sycamore plantations grew more rapidly and accrued more planted tree carbon than the willow oak by an average of ~11 Mg ha^{-1}. The American sycamore plantings were more successful than the willow oaks across all mechanical site preparation treatments. Planted trees were the second largest carbon pool for combined total above and belowground.

Table 4.1 Statistical Comparisons of Carbon Pools of Willow Oak and American Sycamore Established with Site Preparation

Pool	Sycamore		Willow Oak		p value
	Mean (Mg ha^{-1})	% of total C	Mean (Mg ha^{-1})	% of total C	
Planted	*23.55	31%	*12.35	20%	<0.0001
Herbaceous	0.46	1%	0.60	1%	0.7111
Litter	*3.58	5%	*2.56	4%	<0.0001
Fine Roots	*2.41	3%	*1.63	3%	0.0010
Soil Carbon	44.77	60%	45.98	73%	0.3805
Total above	*24.01	32%	*12.95	21%	0.0040
Total below	50.76	68%	50.17	79%	0.9619
Total	*74.77	100%	*63.12	100%	0.0032

*Means are significantly different between planted species (α=0.05)

One minor weakness of our evaluation was that the naturally regenerated trees and shrubs were not included in the evaluation. These data were originally to be collected by another study on the site, but the data were not useable for our evaluation. We do not believe this would change the results as the natural woody regeneration component was relatively minor. To improve aboveground research, a midstory and understory sample should be taken (Bansal et al, 2023). Willow oak plantings did not hold significantly more herbaceous carbon (Table 4.1) but could be allocating more carbon to naturally regenerated trees and shrubs. A more inclusive data set could include root collar diameter, total height, and species of non-planted woody stems, as well as DBH of stems at least 4.5 feet (1.37 m) tall.

Belowground Carbon:

Belowground carbon storage was greater than aboveground carbon within both willow oak and American sycamore plantations (Table 4.1). In both cases, soil carbon to 30 cm was the largest sink of carbon, and accounted for the majority of total carbon across all site preparation

treatments for both species. Although a large amount of carbon was being held in soil, there was no induced difference between soil carbon stored within American sycamore plots and carbon stored in willow oak plots (Table 4.1, $p=0.38$). Although preservation of soil carbon is important for total carbon sequestration, it is not as readily manipulated as aboveground carbon. It may also be too early within the stand development to observe all impacts of on soil carbon accumulation at only 12 years following planting, and subsequent measurements are the best way to determine how soil carbon is being impacted over time (Bansal et al, 2023).

American sycamore plantings had more litter present (Table 4.1, $p\leq0.0001$), likely due to greater numbers of surviving trees, larger trees, and perhaps larger leaves that reduce soil contact. Sycamore had significantly more fine roots to 30 cm depth on average (Table 4.1, $p\leq0.001$), again due to sycamore trees surviving and growing at a higher rate. Our root study was confined to fine roots at 30 cm depth, limiting the conclusions we may draw about the total carbon stored in roots for both American sycamore and willow oak. In terms of total below ground carbon, there was no significant difference between the two species (Table 4.1, $p=0.96$).

Total Carbon:

The majority of the total carbon was found in soil carbon (Table 4.1). While the soil held the most carbon, variations between total carbon of American sycamore and willow oak plots were greatest within the planted overstory. The aboveground carbon in planted trees was the second largest pool, and the most variable, and is more easily manipulated to increase carbon storage as compared to soil carbon.

Planting forests with the specific goal of sequestering carbon is a relatively new concept in forestry, although it matches well with the common goal of managing forests for biomass

production. Past riparian restorations have primarily focused on establishing forests for water quality, wildlife benefits or establishing valuable timber species. The preference for oak on riparian restorations is a continuation of these practices, with oak perceived as having more timber value, and a high wildlife value due to hard mast production (Gardiner et al, 2004). However, when directly compared with the faster growing, riparian pioneer American sycamore, oaks were slower for reforestation of this former agricultural field. American sycamore also proved the more effective species for sequestering carbon, on average holding ~11.5 Mg Ha^{-1} more total carbon (Table 4.1, p=0.0032). At 12 years, American sycamore had higher survival, more growth, and created more forest cover on the floodplain across all site preparation treatments. Results indicate increased planting of American sycamore and other pioneers on riparian reforestation sites would increase survival, growth, and forest establishment (Simmons et al, 2012, Stanturf et al, 2009). While American sycamore does not produce hard mast, American sycamore plantings were more successful, and successful riparian plantings do provide forest habitat, provide nutrients and woody habitat to the stream, shade the stream, and buffer the stream from watershed land uses (Twedt et al, 2002, Stanturf et al, 2004, Simmons et al, 2012).

Use of multiple species in future plantings might allow restorations to both provide forest cover and wildlife values like hard mast. Researchers have experimented with interplanting, and found oak were able to establish underneath a pioneer species overstory (Stanturf et al, 2009, Gardiner et al, 2004). Establishing oaks in the understory or limiting oak planting to well suited microsites would allow for species better suited to be planted across the site, and still provide hard mast from oaks.

Conclusions:

Both willow oak and American sycamore plantings restored riparian forest cover on the former agricultural field due to high survival of the American sycamore and very dense planting of the willow oak. For willow oak, dense planting was the single biggest factor in stocking success. American sycamore was more effective at establishing forest cover and storing carbon than willow oak because it was better suited to the soils and hydrology of the site, as reported by Steel et al. 2021when he evaluated site index for both species. For both American sycamore and willow oak most of the carbon was stored in the mineral soil and all site preparation treatments had similar impacts on soil carbon. There were no clear advantages for any site preparation treatments regarding soil carbon storage. However, species selection and suitability to the site proved to have a greater impact. American sycamore showed significantly higher survival and growth across treatments, allowing sycamore to retain more planted and total carbon than willow oak. Selection of a well suited, fast growing, riparian adapted species and planting adequate numbers to ensure stocking can reduce the need for specialized site preparations to select cases on wet or compacted sites.

Riparian plantings focused on forest establishment and carbon storage should include some proportion of fast-growing, well-suited species. In many instances, the species selection is made on the basis of wildlife preferences rather than site characteristics and species silvics. In these circumstances, additional stems may need to be planted. The establishment of slower growing, marginally suited species like willow oak benefits more from denser plantings than from the considered site preparations. Mortality occurred to some degree on all plots for both species, but the dense plantings still allowed for success in tree stocking in all cases. Willow oak plantings should be used in cases selecting for specific wildlife habitat or sites found to be well

suited for willow oak. Our overall recommendations are to plant sufficient numbers of well-suited species and to use specialized site preparation, if necessary, on wetter or more compacted sites.

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