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Effects of Mechanical Site Preparation, Planting Stock, and Planting Aids on the Survival and Growth of American Sycamore in a Marginal Old Field Riparian Restoration

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Abstract: Survival and growth of planted tree species are common indices used to evaluate success of wetland restoration efforts used to compensate for wetland losses. Restoration efforts on marginal agricultural lands have typically resulted in less than satisfactory survival and growth of desired tree species. In an attempt to determine the effects of bottomland hardwood silvicultural methods on the survival and growth of pioneer tree species, this study evaluated combinations of five mechanical site-preparation techniques (mound, bed, rip, disk, pit), four levels of planting stock (gallon, tubeling, bare root, and direct seed), and three planting aids (mat, tube, none) on the four-year survival and growth of American sycamore planted in an old field riparian area in the Piedmont of Virginia. After four growing seasons, results indicated that mounding mechanical site preparation combined with gallon (3.8 L) planting stock provided the most positive influences on mean survival (100%), height (4.72 m), and groundline diameter (9.52 cm), and resulted in the greatest aboveground dry biomass accumulation (5.44 Mg/ha/year). These treatments may be economically viable for restoration and mitigations efforts, and could offer other economic alternatives such as short-rotation woody crops, which might make restoration efforts in marginal old field areas more attractive to private landowners.

Keywords: silviculture; restoration; site preparation; biomass; sycamore

1. Introduction

Wetlands are a valued resource for water quality, wildlife use, and food/fiber production, yet an estimated 50% of wetlands in the United States have been converted to nonwetlands [1]. The promulgation of the Clean Water Act in 1972 (33 U.S.C. 1251 et seq. §1972) led to regulatory agency mandates to reduce or eliminate the loss of wetlands, often referred to as the "No Net Loss" legislation [2], and the 2008 Compensatory Mitigation Rule created a framework for replacing wetland losses by in-kind replacement, also known as compensatory mitigation, through commercial wetland banks, in-lieu fee programs or by permittee-responsible mitigation projects. The Compensatory Mitigation Rule established guidelines and requirements for satisfactory creation or amelioration of forested wetlands used to replace those that were lost or degraded due to forested wetland losses. An emphasis was placed on establishing wetland viability prior to release of compensatory wetland credits, making commercial mitigation banks the primary method to fulfill wetland mitigation requirements [3]. However, the actual implementation of compensatory wetland and mitigation site design are oftentimes not successful in replacing the functions and values of the permanently impacted wetland. Wetland restoration sites have historically failed due to the mortality of planted wetland tree species [4]. Establishing pioneer tree species on mitigation sites may accelerate the restoration of these

wetland functions and values, and increase compliance with wetland mitigation regulations. Greater emphasis has been placed on the success of planted woody species in these sites, as tree survival and growth are typically limiting factors for long-term site success. Incongruously, commercial forestry operations have been successful in harvesting and planting in wetland areas, such as wet mineral flats and bottomland hardwood areas of the southeastern United States [5]. These techniques are not widely used by wetland design and construction groups within the current compensatory mitigation market [6,7].

Commercial silvicultural techniques may create a less stressful environment that allows for pioneer tree species to become established and rapidly accrue biomass in an environment that would otherwise be dominated by perennial herbaceous species, resulting in herbaceous autogenic dominance [8,9]. Incorporation of pioneer tree species in lieu of late successional woody species, such as *Quercus* spp., has been reported to facilitate woody volunteers and lead to changes in long-term woody species composition and complexity in compensatory wetland sites in the southeastern Piedmont and Coastal Plain [8]. Furthermore, establishment of pioneer species facilitates establishment of slower-growing late successional species, allowing them to mature in environments that would otherwise result in low long-term late successional woody species density and survival.

American sycamore is a resilient, native hardwood species that grows well in old field agricultural areas and other marginal crop areas typically used for mitigation and fiber production [10]. Furthermore, American sycamore have been planted as part of short-rotation woody crop (SRWC) plantations throughout the southeast, particularly in old field areas of the Piedmont ecoregion that are often characterized by high soil compaction, low nutrient content, and wet soil conditions [11,12]. Such areas are often along margins of managed agricultural areas and are frequently unsuitable for crops [13]. Planting trees on these areas may improve soil health by increasing soil organic matter and affiliated soil physical properties, create areas for nutrient cycling, increase biodiversity through additional vegetative cover, and provide additional wildlife habitat. The use of rapid growing species, such as American sycamore, for biomass and bioenergy applications has been recently revisited in the United States and Europe, resulting in a need to quantify the effects of site preparation, planting stock, and planting aids on tree growth response [14]. Marginal old field areas have historically been used for both compensatory mitigation sites and bioenergy production, and both uses rely upon the establishment of woody stock and rapid biomass accumulation for long-term success and meeting site utilization goals.

Mechanical site preparation typically requires the use of heavy equipment to manipulate site soils to optimize site conditions for the establishment of woody species [5]. Site preparation in wetlands is potentially beneficial, as many created forested wetlands fail due to incorrect hydroperiods, such as periods of inundation from excess surface water and groundwater inputs or drought conditions due to groundwater drawdown, and soil compaction [15]. Commercial forestry operations have used mechanical site preparation for decades to prepare harvested sites and to ameliorate the impacts of timber harvesting [6,16,17]. The reduction of soil compaction, creation of site microtopography, and competition control from undesirable species are the primary benefits of mechanical site preparation in forested wetlands [18]. The method of site preparation varies depending upon the location, site conditions, and available machinery. Some of the primary mechanical site preparation methods most often used in areas that have limitations to tree establishment due to hydrologic fluctuations and soil compaction include mounding, bedding, ripping, and disking [17–20].

The type of planting stock is an important factor in the success of mitigation sites that utilize marginal old field areas. Commercial forestry operations traditionally use a variety of planting stock optimized for the specific site conditions. These options typically include direct seeding, year-old (1-0) bare-root seedlings, tubelings, and larger containerized seedlings, typically found in gallon (3.8 L)-sized containers [21]. Tubelings are young seedlings

approximately 30 cm tall with a developed root system that are grown in greenhouse containers. These plants are similar in size and development to a year-old forest seedling. Each of the planting techniques have a cost/benefit associated with it, and a combination of these techniques can be used during the construction and planting of wetland sites [22]. However, compensatory site planning often utilizes the most economical planting stock due to the anticipated need to replant to meet regulatory planting density requirements. Planting stock is used based on the immediate economics of purchasing planting stock, and often ignores the cost to replant or plant, which differs from commercial forest establishment because compensatory mitigation sites often have greater budgets for re-establishment as compared to commercial forestry, but compensatory sites still favor use of a more economical approach that will achieve the required survival [23,24].

Planting aids, such as tree tubes and planting mats, have been utilized to promote survival of seedlings by limiting competition with early successional herbaceous and woody species. These aids may reduce the need for herbicides, which are often prohibited or strictly controlled in wetlands, and the mechanical damage associated with trimmers and mowers [25]. Mechanical and chemical control of herbaceous competition are common for mitigation and bioenergy sites, and are often required for multiple years until woody stock has become established. Options for planting aids include planting tubes and mats, which are cost-effective for installation and maintenance.

Previous studies indicate that mechanical site preparation, type of planting stock, and use of planting aids may be beneficial to the survival and growth of woody species planted in marginal old field settings. Therefore, the goal of this study was to evaluate the effects and interactions of five silvicultural mechanical site preparations, four common planting stock types, and three planting aids, with the overall goal of improving survival and growth of American sycamore in Piedmont old field riparian areas that are suitable for mitigation and fiber/bioenergy sites.

2. Materials and Methods

Field research was conducted at the Reynolds Homestead Forest Resources Research Center, which is located in the Piedmont physiographic province near Critz, Virginia (Figure 1). The area is dominated by former agricultural fields historically used for tobacco cultivation and corn production. The study site is in the riparian area of a first-order perennial unnamed tributary to Mill Creek with a 197-hectare watershed. The study was established on the active floodplain as indicated by field indicators, including drift lines and recent sediment deposits. Observations made by the property manager indicate that the floodplain floods approximately 1 to 3 times per year to a depth of 0.3 to 0.6 meters across the floodplain. Observations during the study supported the property manager's observations. The upland areas of the watershed predominantly comprise mixed upland hardwoods and pine, with interspersed managed pine plantations. Common riparian species include yellow poplar (*Lirodendron tulipifera* L.), American boxelder (*Acer negundo* L.), and red maple (*A. rubrum* L.). The field study area is comprised of two soil types. The primary dominant soil series are French soils, taxonomically classified as fine-loamy over sandy or sandy-skeletal, mixed, active mesic Fluvaquentic Dystrudepts on 0 to 3 percent slopes. The second soil series are Braddock series, taxonomically classified as fine, mixed, semi-active mesic Typic Hapludults on 2% to 8% slopes. Soils are moderately to moderately well drained with colluvium and alluvium parent material. Legacy sediments resulting from European land clearing that was common to the Piedmont region, as described by Trimble [26], are clearly obvious in the soil profiles, which contain buried mineral soil horizons observed throughout the site. Site soils exhibited field hydric soil indicators consistent with wetland soil diagnostic criteria [27]. Annual average temperatures range from 19.4 to 7.2 °C, with average annual rainfall of 1380 mm and snowfall of 290 mm, for a total average annual precipitation of 1670 mm.
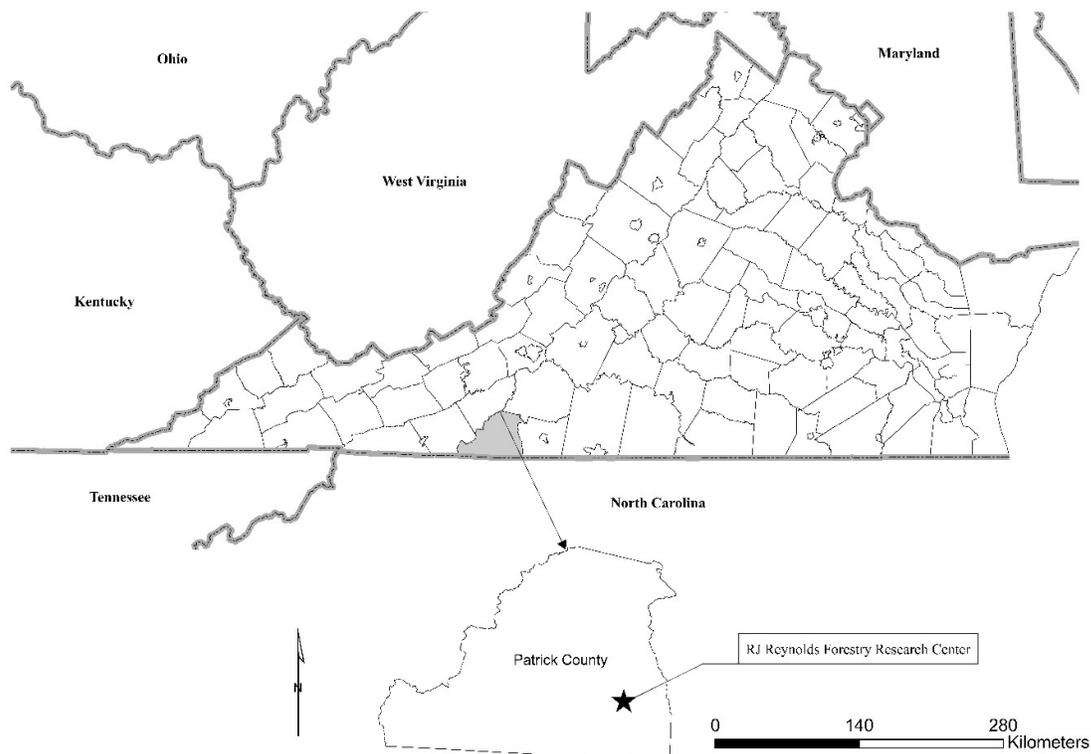
Figure 1. Location of the Reynolds Forestry Research Extension Center, Critz, Virginia.

2.1. Study Layout

Five treatment blocks were established within the old field riparian area to maximize use of the stream floodplain. The blocks were 25.6 m × 29.3 m (0.075 ha), and were established using staff compass and surveyor tape. Corners were marked with rebar and surveyed with a total station. Each site preparation area measured 7.3 m in width, with each block having a length of 29.3 m and an area of 747.5 m (Figure 2). Five mechanical site preparations were established within each of the five blocks: disking, ripping, bedding, pit, and mound. The disk treatment, which is the minimal soil tillage necessary to temporarily reduce competing vegetation and reduce surface compaction, served as the site preparation control. The pit and mound preparations were applied together with the pits situated directly adjacent to the mound. Mound heights and pit depths were approximately 90 cm, with an approximate width of 0.5 m, while bed heights were approximately 50 cm. Combinations of four planting stock types: direct seed, bare root, tubeling, and gallon; and three planting aids: control, tube, and mat, were installed within the mechanical site preparation plots. Four stock types were planted within each of the 12 combinations of seedling type and planting aid (Figure 3). Plantings were on a 1.8 m × 1.2 m grid within the planting area. The study was established at a planting density of 3,200 stems/ha. This planting density was considerably higher than typical riparian plantings within compensatory mitigation sites, but was an acceptable density for bioenergy sites. Planting of the combination of planting stock and planting aids were installed in factorial combination for a total of 48 stems per site-preparation technique.

Mechanical site preparation was conducted in April 2011 and all planting was completed by May 2011. Plantings grids were reestablished after mechanical site preparation and all seed, seedling, tubeling, and gallon-container planting locations were exactly

marked with pin flags. Seeds were planted at a depth of 2.5 cm, and a 2.5 mL scoop of seeds was placed in each seed hole. Seedlings and tubelings were hand-planted with dibble bars, and gallon containers were hand-planted with shovels. All plantings were conducted or supervised by professional foresters in order to ensure proper planting techniques. Due to the old field history of the site, herbaceous competing species were a potential problem, thus glyphosate 4+ (41% glyphosate) (Alligare, LLC, Opelika, Alabama) herbicide was applied to herbaceous species once, in June of the first growing season, and mowing was conducted between June and September of the first growing season. No weed control was conducted after the first year of the study. The weed control was representative of the controls typically employed in bioenergy and mitigation sites.

Figure 2. Experimental block layout, with each block encompassing 747.5 m². Blocks were spaced according to presence of hydric soils within the riparian area.

Gallon (Mat) ▲ ▲ ▲ ▲	Gallon (Control) ▲ ▲ ▲ ▲	Direct Seed (Control) X X X X	Bare Root (Mat) • • • •
Tubeling (Control) ■ ■ ■ ■	Tubeling (Tube) ■ ■ ■ ■	Tubeling (Mat) ■ ■ ■ ■	Direct Seed (Tube) X X X X
Direct Seed (Mat) X X X X	Bare Root (Tube) • • • •	Bare Root (Control) • • • •	Gallon (Tube) ▲ ▲ ▲ ▲

Figure 3. An example of the field layout of one experimental unit containing one site-preparation technique (entire rectangle), and each internal rectangle representing one unit consisting of the planting stock and planting aid treatments. This pattern was repeated five times within each of the five blocks.

2.2. Planting Stock

American sycamore seeds were collected by the project researchers from counties located in both the Piedmont and the Valley and Ridge physiographic provinces of Virginia, and were collected by mechanical removal of the seeds from the tree. Bare root seedlings were obtained from the Virginia Department of Forestry (Crimora, Virginia) and were transported to the site in March 2011. Seeds were cold stratified, and bare-root seedlings were kept refrigerated until planting. Gallon-containerized plants and tubelings were ordered from Wetland Studies and Solutions, Inc (Gainesville, Virginia). Tubelings and gallon-stock seedlings were stored outside in the open and watered daily until planting. All seedlings, tubelings, and gallon-container trees were 1-0 planting stock.

2.3. Planting Aids

The mats were 1 m² VisPore mats (Landscape Supply, Inc., Roanoke, Virginia), and were installed with steel landscape staples. Tubes were 1 m Tubex Standard Tree Shelters (Tubex USA, Old Hickory, Tennessee), and were installed using a 1 m wooden support stake. Planting aids were installed in June 2011 after planting and before weed-control measures were initiated.

2.4. Data Collection and Analysis

Survival, ground line diameter, diameter at breast height (dbh), and height were collected at the end of each growing season beginning in January 2012. Successful germination of seeds or survival of seedlings were visually evaluated during each data collection. Ground line diameter and dbh (mm) for each stem were collected to the nearest 0.1 mm using digital calipers. Total height (m) was collected using a height pole to the nearest 2.5 cm. Stem volume was calculated based on the volume of a simple cylinder, where volume (cm^3) = diameter^2 (cm) × height (cm). Dry-weight biomass for the total stem above stump height (10 cm) was calculated for year 3 and year 4 to determine whole-tree dry mass at the plot level (kg/m²) and scaled to Mg/ha [28]. Aboveground net primary production

(ANPP*wood* in Mg/ha/year) was calculated from the difference in aboveground biomass between years 3 and 4.

The experimental design was a split plot within a randomized complete block design to evaluate the treatment and interaction effects on survival and growth [29]. The mechanical site-preparation techniques constituted the whole plot, while the combinations of plant stock type and planting aids provided the split treatment. All treatment combinations were applied during the study, but shortages in planting stock due to low gallon-stock availability and low availability of the VisPore matting and Tubex tree shelters during planting-aid installation compromised the original design and resulted in a planted n = 960. Statistical analysis was conducted using JMP Pro version 14.2.0 [30]. Least-square means were generated using the REML analysis, and multiple comparisons among means were calculated using Tukey's post hoc HSD. An alpha level of 0.05 was applied to indicate statistical significance. The assumption that data were normally distributed with constant variance was tested using studentized residuals comparison to predicted values to test for constant variance and normal quantile plots to test for normal data distribution. Data were determined to have constant variance and normal distribution. Only surviving stems were included in diameter, height, and biomass calculations.

3. Results

3.1. Site Preparation Treatments

In general, mounding resulted in the best survival and growth performance. Year 1 survival was greatest in mound (69.2%) and disk (69.2%), and lowest in the pit (59.2%) treatment (p = 0.0172), but site preparation did not have a significant impact on survival in the remaining years (Table 1). Mounding had the largest growth indices across all years, followed by bedding. The pit treatment had the lowest growth indices across all measures. Mounding produced 20% and 25% greater height than bedding and pit, respectfully (Table 2); almost 30% greater groundline diameter than bedding and 40% greater groundline diameter than pit (Table 3); and more than 25% and 40% greater dbh than ripping and pit, respectfully (Table 4). Total dry-stem biomass (Table 5) was 40% greater in the mound treatment than ripping, which had the next largest average biomass. Mounding was 80% greater than disking, which had the lowest average dry-stem biomass accumulation. The rip treatment groundline diameter, dbh, and biomass growth indices steadily increased after year 1, and were statistically similar to the mound treatment by year 4. Mound ANPP*wood* (2.62 Mg/ha/yr) was significantly greater than the bed (1.43 Mg/ha/yr), disk (0.92 Mg/ha/yr) and pit (1.13 Mg/ha/yr) treatments, with no difference observed between mound and rip (1.68 Mg/ha/yr) treatments (Table 5).

Table 1. Average percent survival (SE) for American sycamore in the Virginia Piedmont by site preparation, planting stock type, and planting aid. Values with different letters indicate statistically significant differences according to Tukey's post hoc HSD (p < 0.05). Bolded text indicates treatment category.

Treatment	Year 1	Year 2	Year 3	Year 4
Site Preparation	*p = 0.0172*	*p = 0.3351*	*p = 0.3937*	*p = 0.0378*
Mound	69.2 (10.1) [a]	68.3 (10.4)	68.3 (10.4)	68.3 (10.1) [a]
Disk	69.2 (10.8) [a]	67.5 (11.6)	66.7 (11.8)	66.7 (11.8) [ab]
Bed	65.4 (9.5) [ab]	65.0 (9.5)	65.4 (9.6)	65.0 (9.8) [ab]
Rip	68.1 (10.1) [ab]	67.7 (10.3)	67.1 (10.3)	67.5 (10.1) [ab]
Pit	59.2 (12.3) [b]	60.8 (10.3)	60.8 (12.3)	60.0 (12.1) [b]
Planting Stock	*p < 0.0001*	*p < 0.0001*	*p < 0.0001*	*p < 0.0001*
Gallon	99.7 (0.3) [a]	99.7 (0.3) [a]	99.3 (0.4) [a]	99.3 (0.4) [a]
Tubeling	93.0 (1.4) [a]	93.7 (1.5) [a]	94.0 (1.3) [a]	93.3 (1.3) [a]
Bare Root	57.7 (4.7) [b]	58.0 (4.4) [b]	57.7 (4.3) [b]	57.7 (4.3) [b]
Direct Seed	14.5 (2.2) [c]	12.2 (2.2) [c]	11.7 (2.4) [c]	11.7 (2.2) [c]

Planting Aid	*p = 0.2089*	*p = 0.1874*	*p = 0.2676*	*p = 0.3480*
Tube	68.5 (8.3)	68.2 (8.4)	67.5 (8.4)	67.2 (8.4)
Mat	66.0 (7.8)	66.7 (7.8)	66.7 (7.8)	66.2 (7.7)
None	64.1 (8.2)	62.6 (8.6)	62.7 (8.7)	63.0 (8.6)

Table 2. Average height (m) (SE) for American sycamore in the Virginia Piedmont by site preparation, planting stock type, and planting aid. Values with different letters indicate statistically significant differences according to Tukey's post hoc HSD (*p* < 0.05). Bolded text indicates treatment category.

Treatment	Year 1	Year 2	Year 3	Year 4
Site Preparation	*p = 0.0017*	*p < 0.0001*	*p = 0.0044*	*p = 0.0002*
Mound	2.16 (0.12) [a]	2.87 (0.14) [a]	3.65 (0.19) [a]	5.10 (0.25) [a]
Bed	1.73 (0.12) [b]	2.22 (0.14) [b]	2.89 (0.18) [b]	4.00 (0.27) [b]
Rip	1.75 (0.11) [b]	2.31 (0.14) [b]	3.26 (0.20) [b]	4.27 (0.28) [b]
Disk	1.62 (0.11) [b]	1.99 (0.16) [b]	2.51 (0.22) [b]	3.56 (0.27) [b]
Pit	1.75 (0.10) [b]	2.08 (0.16) [b]	2.79 (0.22) [b]	4.24 (0.30) [b]
Planting Stock	*p < 0.0001*	*p < 0.0001*	*p < 0.0001*	*p < 0.0001*
Gallon	2.30 (0.08) [a]	3.15 (0.12) [a]	3.97 (0.17) [a]	5.05 (0.21) [a]
Tubeling	1.88 (0.08) [b]	2.70 (0.12) [b]	3.26 (0.16) [b]	4.43 (0.21) [b]
Bare Root	1.57 (0.08) [c]	2.25 (0.13) [c]	2.91 (0.17) [c]	3.80 (0.22) [c]
Direct Seed	0.69 (0.11) [d]	1.19 (0.19) [d]	1.68 (0.26) [d]	2.39 (0.36) [d]
Planting Aid	*p = 0.1788*	*p = 0.1131*	*p = 0.1226*	*p = 0.1677*
Tube	1.79 (0.08)	2.49 (0.12)	3.19 (0.17)	4.16 (0.22)
Mat	1.87 (0.10)	2.70 (0.13)	3.47 (0.16)	4.47 (0.21)
None	1.74 (0.10)	2.48 (0.14)	3.17 (0.18)	4.08 (0.22)

Table 3. Average groundline diameter (cm) (SE) for American sycamore in the Virginia Piedmont by site preparation, planting stock type, and planting aid. Values with different letters indicate statistically significant differences according to Tukey's post hoc HSD (*p* < 0.05). Bolded text indicates treatment category.

Treatment	Year 1	Year 2	Year 3	Year 4
Site Preparation	*p < 0.0001*	*p = 0.0002*	*p = 0.0003*	*p = 0.0002*
Mound	3.22 (0.21) [a]	4.56 (0.26) [a]	5.94 (0.32) [a]	7.48 (0.42) [a]
Bed	2.47 (0.20) [b]	3.36 (0.29) [b]	4.37 (0.36) [b]	5.35 (0.45) [b]
Rip	2.42 (0.16) [b]	3.29 (0.25) [b]	4.50 (0.33) [b]	5.61 (0.41) [ab]
Disk	2.22 (0.15) [b]	2.99 (0.220 [b]	3.85 (0.27) [b]	4.60 (0.34) [b]
Pit	2.13 (0.17) [b]	2.77 (0.23) [b]	3.75 (0.33) [b]	4.43 (0.42) [b]
Planting Stock	*p < 0.0001*	*p < 0.0001*	*p < 0.0001*	*p < 0.0001*
Gallon	3.46 (0.13) [a]	4.52 (0.20) [a]	5.76 (0.22) [a]	7.02 (0.36) [a]
Tubeling	2.56 (0.12) [b]	3.45 (0.19) [b]	4.58 (0.25) [b]	5.69 (0.32) [b]
Bare Root	1.95 (0.11) [c]	2.78 (0.17) [c]	3.69 (0.22) [c]	4.48 (0.29) [c]
Direct Seed	0.89 (0.12) [d]	1.43 (0.24) [d]	2.19 (0.31) [d]	2.78 (0.39) [d]
Planting Aid	*p = 0.0014*	*p = 0.0158*	*p = 0.0594*	*p = 0.2007*
Tube	2.17 (0.13) [b]	3.06 (0.20) [b]	4.12 (0.27)	5.22 (0.36)
Mat	2.76 (0.15) [a]	3.73 (0.21) [a]	4.84 (0.27)	5.84 (0.33)
None	2.58 (0.15) [ab]	3.43 (0.20) [ab]	4.55 (0.25)	5.53 (0.32)

Table 4. Average dbh (cm) (SE) for American sycamore in the Virginia Piedmont by site preparation, planting stock type, and planting aid. Values with different letters indicate statistically significant differences according to Tukey's post hoc HSD (*p* < 0.05). Bolded text indicates treatment category.

Treatment	Year 1	Year 2	Year 3	Year 4
Site Preparation	*p = 0.0040*	*p = 0.0027*	*p = 0.0024*	*p = 0.0007*
Mound	1.21 (0.11) [a]	2.40 (0.21) [a]	3.18 (0.21) [a]	4.31 (0.25) [a]
Bed	0.77 (0.10) [b]	1.46 90.17)	2.12 (0.22) [b]	2.87 (0.27) [b]
Rip	0.81 (0.09) [ab]	1.19 (0.16) [ab]	2.28 (0.22) [ab]	3.15 (0.27) [ab]

Disk	0.72 (0.09) [ab]	1.37 (0.15) [b]	1.87 (0.19) [b]	2.49 (0.23) [b]
Pit	0.64 (0.09) [b]	1.39 (0.17) [b]	1.96 (0.22) [b]	2.68 (0.30) [b]
Planting Stock	*p < 0.0001*	*p < 0.0001*	*p < 0.0001*	*p < 0.0001*
Gallon	1.22 (0.08) [a]	2.21 (0.14) [a]	2.97 (0.18) [a]	3.93 (0.22) [a]
Tubeling	0.85 (0.07) [b]	1.73 (0.15) [b]	2.36 (0.16) [b]	3.23 (0.21) [ab]
Bare Root	0.61 (0.07) [b]	1.28 (0.16) [bc]	1.90 (0.16) [b]	2.59 (0.20) [bc]
Direct Seed	0.10 (0.06) [c]	0.43 (0.15) [c]	0.82 (0.22) [c]	1.36 (0.27) [c]
Planting Aid	*p = 0.6563*	*p = 0.3868*	*p = 0.3695*	*p = 0.3720*
Tube	0.81 (0.08)	1.56 (0.13)	2.18 (0.18)	3.01 (0.23)
Mat	0.87 (0.08)	1.76 (0.16)	2.41 (0.18)	3.26 (0.22)
None	0.83 (0.08)	1.62 (0.13)	2.28 (0.16)	3.06 (0.20)

Table 5. Average (Mg/ha) (SE) dry-weight biomass and ANPP*wood* (Mg/ha/year) for American sycamore in the Virginia Piedmont by site preparation, planting stock type, and planting aid. Values with different letters indicate statistically significant differences according to Tukey's post hoc HSD (*p* < 0.05). Bolded text indicates treatment category.

	Average Biomass (Mg/ha)		ANPP*wood* (Mg/ha/year)
Treatment	**Year 3**	**Year 4**	
Site Preparation	*p = 0.0117*	*p = 0.0011*	*p = 0.0002*
Mound	2.01 (0.33) [a]	4.62 (0.72) [a]	2.62 (0.41) [a]
Bed	1.36 (0.36) [ab]	2.79 (0.68) [ab]	1.43 (0.33)
Rip	1.33 (0.25) [ab]	3.01 (0.54) [ab]	1.68 (0.29) [ab]
Disk	0.91 (0.26) [b]	1.84 (0.48) [b]	0.92 (0.23) [b]
Pit	0.84 (0.24) [b]	1.97 (0.52) [b]	1.13 (0.29) [b]
Planting Stock	*p < 0.0001*	*p < 0.0001*	*p < 0.0001*
Gallon	2.83 (0.38) [a]	6.02 (0.75) [a]	3.19 (0.38) [a]
Tubeling	1.60 (0.22) [b]	3.70 (0.48) [b]	2.10 (0.28) [b]
Bare Root	0.55 (0.09) [c]	1.28 (0.23) [c]	0.72 (0.14) [c]
Direct Seed	0.03 (0.02) [c]	0.09 (0.03) [c]	0.06 (0.02) [c]
Planting Aid	*p = 0.3695*	*p = 0.3629*	*p = 0.2926*
Tube	1.36 (0.27)	3.14 (0.56)	1.78 (0.30)
Mat	1.46 (0.24)	3.13 (0.49)	1.67 (0.26)
None	1.06 (0.17)	2.33 (0.35)	1.24 (0.19)

3.2. Planting Stock

Year 1 average survival was greatest in gallon (99.7%) and tubeling (93.0%), and lowest in direct seed (14.5%) (*p* < 0.0001) (Table 1). Average tree height showed a strong significant relationship with planting stock in all years (*p* < 0.0001). Gallon planting stock was 75% taller than direct seed, 30% taller than bare root, and 20% taller than tubeling stock in years 1, 2, and 3. The wide height discrepancy was maintained between gallon stock and bare root in year 4, but was reduced to 20% taller than bare root and within 10% of tubeling height. Tubeling heights were also significantly greater than bare root and direct seed in all years (Table 2). Average groundline diameters were significantly different across all years (*p* < 0.0001), with gallon and tubeling planting stock over double the average diameter of bare root (Table 3). Planting stock had a significant effect on average dbh across all years (*p* < 0.0001), with gallon and tubeling planting stock dbh significantly greater than bare root and direct seed across (Table 4). Gallon planting stock showed significantly greater year 4 biomass (6.02 Mg/ha) than all other planting stock (*p* < 0.0001). ANPP*wood* was significantly greater with gallon planting stock (3.19 Mg/ha/year) than all other planting stocks (Table 5).

3.3. Planting Aids

The effects of planting aids on survival were not significantly different (*p* = 0.2089) (Table 1). Planting aids did not significantly affect tree height for any year (Table 2). Planting aids had a significant relationship with average groundline diameter in year 1 and 2, with matting having significantly greater diameter than tree tubes. No significant difference was observed between no planting aid and matting (Table 3). No significant effect was observed for dbh for any year (Table 4). No significant effects were observed for biomass or ANPP*wood* from matting, tree tubes, or no treatment applications (Table 5).

3.4. Interaction Effects

For survival, a significant interaction effect in all years was observed between site preparation and planting stock. Gallon and tubeling planting stock combined with the mound site preparation had survival rates ranging from 97% (tubeling) to 100% (gallon) for all four years. No significant interactions were observed for average height, average groundline diameter, average dbh, average biomass, or ANPP*wood*. Interaction effects means are provided in supplemental Tables S1–S5.

4. Discussion

The high woody-stem mortality often associated with compensatory mitigation sites can often be traced to marginal existing site conditions and improper species selection of planting stock [4,31]. The observed survival and biomass results of this study indicated that the appropriate species selection, application of site-preparation techniques, and use of appropriate planting stock type can increase survival and growth within old field and marginal agricultural sites in the Piedmont of Virginia. Based upon evaluation of the site using the Baker and Broadfoot site index model [32], which evaluates soil and site factors as indicators of soil aeration, moisture, compaction, and nutrients, the site was considered marginal for most hardwood species due to the cumulative impacts of high-intensity agriculture at the site. Site index (base age 50) was approximately 70 to 75 feet (21 to 23 m) for American sycamore, which indicated that these species were more suitable for the observed site conditions. Selection of American sycamore for the site was further validated, as mature sycamore were also observed immediately downstream from the research property within existing woody riparian and wetland areas in the watershed.

The survival rates observed in this study for both site preparation and planting stock were much higher than in previous studies of sycamore survival in compensatory mitigation sites, which ranged from 59% to 45% after 4 years [4,33]. Overall, mortality was greatest during year 1, with no significant differences in survival observed between the remaining years of the study. This trend was similar to previously observed mortality rates, which were greatest in the first three years after planting [33,34]. The high survival rates of gallon and tubeling stock have historically been attributed to greater groundline diameter, root development, and hydrologic resilience [35]. Site preparations such as mounding, bedding, and ripping reduced soil compaction inherent in marginal agricultural field settings and increased survival [17,20]. The combined effect of site preparation and stock type, specifically mounding, bedding, and gallon or tubeling stock types, favored very high survival and biomass accumulation rate. Higher survival rates could be attributed to mounding and bedding reducing inundation-related mortality and increased root volume, resulting in greater soil moisture availability during periods of low precipitation. American sycamore seedlings are more resilient to inundation during establishment than other bottomland hardwood species, but are more susceptible to dry hydrologic conditions [36,37]. Gallon and tubeling stock types increased resilience likely by increasing root growth potential and reduced transplant shock [35,38].

Tree growth indices, as measured by average height, groundline diameter, and dbh, were highest in the lowest-mortality treatments. Mounding site preparation was signifi-

cantly greater than all other site-preparation techniques through year 4, and directly supported greater hydrologic resilience for planted stock in marginal agricultural areas. Gallon and tubeling stock were consistently greater in all areas of tree growth, and met regulatory success criteria for tree height and canopy closure prior to year 3 of the study. Planting aids, which are commonly used in marginal land restoration programs such as the Conservation Reserve Enhancement Program, did not provide any significant benefit beyond year 3, which was consistent with previous research [39]. The observed results supported use of site preparation, particularly mounding and bedding, in combination with gallon and tubeling planting stock, to expedite tree growth to meet site success criteria. Ripping may also be a viable site-preparation technique for meeting longer timeline success criteria.

Economically, the use of site-preparation techniques and planting stock accelerate meeting site success criteria, thus increasing the availability of wetland and buffer credits, which are typically available starting in year 3 after planting on sites that meet regulatory success criteria. Typical costs for site preparation range from USD 182 to 286 per acre (USD 358 to 623/hectare) in 2018, with mounding having a higher cost than bedding or ripping due to the lower equipment efficiency and the amount of earthwork required [39]. Planting costs vary widely, with gallon plants typically an order of magnitude more expensive than bare-root plants [33]. However, American sycamore tubeling planting stock are similarly priced to bare-root planting stock, and the cost of hand-planting ranged from USD 60 to 112 per acre (USD 136 to 178/ha) in 2018 at an average of 580 seedlings per acre [40,41]. Comparatively, the price for compensatory wetland and buffer credits ranges from USD 52,000 to 100,000 per acre (USD 128,000 to 247,000/ha) for in-lieu fee advance Piedmont wetland credits in Virginia and North Carolina [42,43]. Commercial wetland credits are typically more expensive than in-lieu fee credits, with value fluctuating with market demand. These credits are often produced in regions that do not have in-lieu fee advance credits available, and typically wetland mitigation credits are required to encompass more area than the credit value, which increases commercial wetland credit cost as land values increase [44].

Under current regulatory conditions, wetland and buffer credits are released for sale if site conditions meet success criteria, which generally include stem density and growth indices requirements by the third and fifth years after planting. Based upon our study results, implementation of site-preparation techniques and planting gallon or tubeling stock could potentially increase the likelihood of attaining required stem-density success criteria. Traditionally, bare-root planting stock has been the preferred planting stock due to the low cost of stock and planting in comparison to more mature planting stock. However, the results of this study indicated that bare-root planting stock generally does not meet regulatory thresholds for success for stem density or growth, and due to the lower survival rates observed, requires greater investment in replanting, which will delay the credit release schedule and reduce the financial incentive to create wetland areas in compensatory mitigation sites. Limited compensatory credit supply has the potential to increase costs per wetland credit, which may stress the current regulatory "no net loss" goals and may reduce both economic returns and ecological benefits.

Our results demonstrated that dry-stem biomass values from using mounding combined with gallon and tubeling planting stock produced between 3.3 and 5.4 Mg/ha/yr on Piedmont old field marginal agricultural sites, at a planting density of 3,200 stems/ha, without the use of irrigation, fertilizers, or other silvicultural inputs after establishment (Tables 3–5). These values were within the range of previous studies that did not conduct mechanical site preparation using higher planting densities of 5000 to 10,000 trees/ha [44]. The dry stem biomass values observed were most likely underestimated, since the biomass of leaves and branches were not included in our study [33,45–47]. This study is unique in assessing site preparation and planting stock in lieu of high inputs (irrigation, fertilizer, chemical applications) and increased planting density. Typically, high inputs are used to decrease the growth period of planted stock in order increase the economic

viability of marginal land SRWC plots, for which it is estimated that a biomass production of 8 to 10 Mg/ha is required for economic viability [48].

Tubeling and gallon planting stock returned biomass values greater than three times the bare-root dry biomass, and when site preparation and planting stock treatments were combined, all combinations of site preparation and gallon or tubeling stock outperformed bare-root stock. Traditionally, bare-root planting stock is the predominant planting method, which is coupled with high input silvicultural management methods, including fertilizer and irrigation. The results of this study indicated that use of larger planting stock and any site-preparation method except pitting will increase dry biomass and increase the economic viability of marginal lands for bioenergy production.

5. Conclusions

Marginal agricultural lands in the Piedmont are often less suitable for row crop agriculture, and stream properties may be degraded if landowners choose to manage such areas for livestock production. Agricultural production in the smaller Piedmont floodplains is of restricted ecological and economic benefits to landowners or the environment if they remain as marginal agricultural lands. Use of marginal agricultural areas for compensatory mitigation or SRWC production may increase the environmental and economic viability of the sites and may also increase the willingness of landowners to partition historically low-productivity lands for applications that increase the net ecological landscape benefit. American sycamore is a native and common species in naturally regenerated stands in Piedmont riparian areas, and the species has a high tolerance for environmental stressors and use of site-preparation techniques, specifically mounding and bedding, and larger planting stock to further increase establishment will increase productivity at a potentially acceptable relatively minimal cost for the economic return to landowners and bioenergy producers. The combination of site preparation and larger planting stock increased productivity of American sycamore on marginal agricultural lands to levels typically observed with high-input SRWS management practices. Using larger planting stock and implementing site-preparation techniques decrease the negative effects of soil compaction, excessive soil wetness, and unpredictable precipitation, and increase early root establishment, which increases biomass production. The biomass increases observed at relatively low planting density illustrated the viability of these silvicultural applications. Further investigation into increased planting density and long-term sustainability of marginal lands for sycamore biomass production are needed to determine the most suitable management practices for optimization of ecological and economic services for marginal lands. Increasing the economic viability may provide more opportunity to utilize these areas for a net positive ecological gain by increasing landscape ecosystem services. Although failures are relatively common for wetland mitigation and restoration projects, these results emphasize that wetland restoration on such sites can be achieved through a combination of silvicultural manipulations (early weed control, species selection, planting supervision, mechanical site preparation, large seedlings) that address site limitations (compaction, drainage, competition).

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