Assessment of Woody Vegetation for Replacement of Ecological Functions in Created Forested Wetlands of the Piedmont Province of Virginia

2013 Annual Report
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PIEDMONT WETLANDS RESEARCH PROGRAM

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Executive Summary

Poor survival and/or slow growth rates of woody vegetation planted in created forested wetlands have been a major cause of poor performance of these wetlands. The purpose of our work is twofold: to establish a Mesocosm and Field study to 1) measure the performance of several woody species and stocktypes and 2) determine the ability of planted trees to perform ecological functions.

Three objectives were proposed to address these questions:

1. to critically evaluate and improve upon the planting of woody vegetation in created forested headwater wetlands in the Piedmont Province, Virginia.
2. determine the appropriate vegetative measures that will identify whether the important wetland functions are being replaced.
3. compile an updated literature review concerning created palustrine wetlands.

In 2009 a Mesocosm site was established at the New Kent Forestry Center, in Providence Forge, VA. The site was divided into three hydrologically distinct cells. At the same time, three Piedmont constructed wetland field sites were chosen for the study and are comprised of the three phases (Designated as Phase I, II, and III) of the Loudoun County Wetland and Stream Mitigation Bank that were designed and installed by Wetland Studies and Solutions, Inc**.**

This report presents results after five growing seasons. Results from the Mesocosm and Field site suggest that the initial difference in growth among the stocktypes diminishes as time progresses. In general, the primary successional species grown in gallon containers meet the ecological performance standards established for Virginia. However, the cost analysis of planting suggests that a mixture of primary and secondary species grown as bare root may be the most economical choice. When combining the morphology, growth, and economic analysis it appears that a primary (excluding *P. occidentalis*) species planted as bare root and gallons and secondary species grown as gallon stocktype would be the most appropriate for establishing trees in created forested wetlands.

In 2013, two talks were presented at local and international conferences by graduate and undergraduate students from VIMS and CNU (Appendix 4). Seven undergraduates completed research projects at the Mesocosm during the summer and fall of 2013. Over five years ~175 students, Master Naturalist, Master Gardeners, Boy Scouts and Girl Scouts have visited and helped collect data at the Mesocosm. Currently two CNU graduate students are designing their thesis at the Field site and one Ph.D. student is currently implementing his dissertation research at the Mesocosm. Finally, one publication has been submitted to Ecological Engineering.

Introduction and Project Description

Poor survival and/or slow growth rates of woody vegetation planted in created forested wetlands have been a major cause of poor performance of these wetlands (NRDC 1995, Spieles 2005, Leo Snead, Virginia Dept. Transportation, Richmond, VA, pers. comm.). There are numerous species of woody plants and stocktypes (e.g. seeds, bare-root seedling, tubelings, 1 or 3 gal. potted) available for planting. However, there are few data driven studies that have addressed how the choice of quality (or size), quantity, species diversity of woody plants and associated planting methods affects the survival and growth of woody species in created wetlands. Therefore, restoration managers lack data to quantify the ability of created forested wetlands to achieve structural or functional maturity. The purpose of our work is twofold: to establish a Mesocosm and Field study to 1) measure the performance of several woody species and stocktypes and 2) determine the ability of created wetlands to perform lost wetland functions such as biomass and productivity that have been described by Odum (1969) as requirements for ecosystem development.

Objectives and Background

This study has three main objectives that are described below with additional background information.

Objective 1

The first objective of this study is to critically evaluate and improve upon the planting of woody vegetation in created forested headwater wetlands in the Piedmont Province, Virginia. The purpose of this objective is to identify the most appropriate woody species and stocktype(s) to recommend for planting in created forested wetlands in the Piedmont Province of Virginia.

Background – Objective 1

Most woody planting into forested wetlands relies on one of three methods of planting stock. Bare-root seedlings, the most common form planted, are young saplings (~1 year old) with no soil in the root-ball. Tubelings are similar to bare-root with the exception of a slightly larger rootstock. Potted plants come in various sizes (from 1 to 5 gallons or larger), can be from 1 to several years old in the larger pots, and contain a well formed root-ball, presumably with associated microfauna. The three types differ in price with potted plants often 5 to 10 times more expensive to buy and more labor intensive to plant. This study also seeks to determine if the added growth and more rapid ecological development justify the expense of potted plants. We will attempt to fulfill the latter part of the objective in an addendum to this report.

The second part of this objective is to determine whether certain species are more appropriate to plant than others. Certain hardwood species, such as oaks, are slow growing and appear later in the forest succession processes, typically many years after the canopy closes (Whittaker 1978). Spencer et al. (2001) showed that pioneer species such as *Salix nigra* (black willow) and *Betula nigra* (river birch) were the first colonizers in timbered forested wetlands in Virginia, with oak and hickory appearing after approximately 15 years, usually as coppice species. DeBerry and Perry (2012) concluded that the design methods used to construct forested wetlands lend themselves to the establishment of woody species that colonize during dry conditions but can rapidly adapt to prolonged saturation or inundation and recommended planting species such *Platanus occidentalis* (American sycamore), *S. nigra*, and *Taxodium distichum* (bald cypress). In this study, we are evaluating the performance of seven woody species common to the forested wetlands of the Piedmont (*B. nigra*, *Liquidambar styraciflua*, *P. occidentalis, Quercus bicolor, Q. palustris, Q. phellos*, and *S. nigra*) in a coordinated Mesocosm and Field study by comparing survival and growth rates (via morphometric assessment) of tree (sapling) plantings: 1) from various stocktypes (as bare-root seedlings, tubelings, and one gallon pots) and 2) several species under three distinct hydrologic conditions: mesic (Ideal cell), saturated in the root zone (top 20cm) during winter, fall and spring (Saturated cell), and inundated throughout the year (Flooded cell). Only the Saturated cell conditions are meant to mimic natural conditions. The Ideal and Flooded cell conditions are meant to provide data that will allow us to determine optimal, least hydrological stressed (Ideal cell) and harshest, most hydrological stressed (Flooded cell) survival and growth conditions for the seven woody species. The data collected from these latter treatments will be used to determine upper (Ideal) and lower (Flooded) limits of survival and growth that would be expect in the Saturated cell and the Loudon Co. Field data. These species can be divided into two groups: fast growing pioneer species (*B. nigra*, *L. styraciflua*, *P. occidentalis* and *S. nigra*) and slow growing secondary succession species (*Q. bicolor*, *Q. palustris,* and *Q. phellos*) (Radford et al. 1976, Gleason and Cronquest 1998, Spencer et al. 2001). In the future we propose to test species that have undergone specific initial growth processes (e.g. RPM, flood or inundation hardening, fertilization).

Objective 2

The second objective of this study is to determine the appropriate vegetative measures that will identify whether the important wetland functions are being replaced. The purpose of this objective are to relate woody growth (via morphometric analysis) as a dependent variable to two independent ecological variables (above and belowground biomass, net ecosystem exchange NEE), to determine vegetation similarity of created forested wetlands and reference sites, and to determine the role of volunteer woody species. The data also will provide information that will support Objective 1; i.e. what is (are) the most effective species to plant (based on maximum growth and maximum CO_2 fixation efficiency).

Background – Objective 2

Odum (1969) identified (above and below ground) biomass and net primary productivity as two major functions of wetland ecosystem development. However, measuring each of these functions in the field is time consuming and destructive (i.e. requires cutting and removing of vegetation). Therefore, many authors and regulators have turned to non-destructive measures of vegetation, such as cover and/or density, as a proxy for assessing the presence and quality of the biomass and productivity functions in wetlands (Brinson 1993, Perry and Hershner 1999).

Other structural attributes that have been used to quantify woody vegetation and tied to biomass include height, number of branches, length of branches, and basal area (Mueller-Dombois and Ellenberg 1974, Day 1985, Spencer et al. 2001, Bailey et al. 2007). However, few studies have related these structural attributes to growth rates and, therefore, productivity. Bailey et al. (2007) found individual canopy cover (measured with a caliper), stem diameter at the soil level, and maximum height were the best predictors of sapling growth in a created forested wetland in Virginia of seven possible morphological measurements taken for woody vegetation. Structural data can also be used to calculate species diversity as an integration of evenness and richness (Mueller-Dombois and Ellenberg 1974), while a simple species list can be used to calculate metrics such as Simpson's or Jaccard's indices of similarity (Mueller-Dombois and Ellenberg 1974).

We used the methods developed by Bailey et al. (2007) to determine the growth of planted woody vegetation at both the Mesocosm and three Field sites. The Mesocosm cells also are being used to compare the growth to two ecological functions: plant biomass and overall productivity. Above and belowground biomass was measured by sacrificing three (3) individuals of each species and stocktype in winter of 2010. Net Ecosystem Exchange (carbon flux) was measured with a PP Systems TPS-2 Portable Gas Analyzer (a measure of efficiency in CO_2 fixation) in July 2010 (Bailey 2006, Cornell et al. 2007).

Two other tasks in this objective included: 1) determining the role volunteer woody plants in created forested wetlands by using a chronosequence of sites in the Piedmont and 2) determining the distribution of volunteer species in the created systems. We plan to quantitatively determine the woody species occurrence and diversity and ecological functions in Virginia Piedmont reference wetlands, and to compare them to created wetlands planted with various stocktypes, sizes and species mixes.

Objective 3

The third objective of this study was to complete an in-depth literature review.

Background – Objective 3

We have continued to update available literature for available technologies for planting woody vegetation, survival reports, evaluations of ecological potential, and recommendations regarding species for created forested wetlands. This included, but was not limited to:

1. Current planting practices that are acceptable to regulatory agencies and utilized by consultants in Virginia for creating forested wetlands (i.e., determining quantity, stock size and species mix that are being used);
2. Existing use and success of incorporating a woody pioneer species (e.g., *Betula* spp., *L. styraciflua*, *Salix* spp.) for forested wetland creation; and,
3. Alternative methods to enhance establishment and growth of woody species (i.e., mycorrhizal inoculations, root production method (RPM) trees, colonization from adjacent property, etc.).

Preliminary Studies

Our initial work in eastern Virginia (Spencer et al. 2001) found that disturbed forested wetland systems did not proceed through primary succession processes after a disturbance (timbering in the study), but became re-vegetated through a combination of coppicing (a secondary succession process) and the establishment of nurse species (a primary succession process). This suggests that afforestation of created forested wetlands must begin with nurse species such as American sycamore, black willow, and river birch which can then facilitate oak and hickory establishment. DeBerry (2006) and DeBerry and Perry (2012) reported the same processes in created forested wetlands in the Piedmont and Coastal Plain of Virginia. A few of the late successional species and most of the nurse species in that study survived after 10 to 15 years. The proposed study builds on that work to quantify growth and establish ranges for future growth rate curves.

Dickenson (2007), working with Drs. Perry and Daniels in a created tidal freshwater swamp, documented that *Taxodium distichum* tubelings showed increase root and stem length when grown on a 15cm (6in) ridge v. those at soil level or in 15cm ditches. Bailey et al. (2007) came to similar conclusions in a created hardwood swamp: small changes in the elevation altered tree growth. Therefore, it is important to choose species that can tolerate the stress of a given wetland environment. DeBerry and Perry (2012) conclude that the process of creating a wetland, that of planting in the dry and then flooding the habitat, mimics the hydrologic process preferred by certain early-successional species. They specifically noted the potential role of American sycamore, black willow, and bald cypress for afforestation in the Piedmont and Coastal Plain of Virginia.

Principal sources of stress in the Piedmont Province are derived from soil texture and hydroperiod. The clayey soils common to the Piedmont are frequently uncovered when earthwork is conducted and provide a challenging growth medium for most tree species (Atkinson et al. 2005). Anoxic soil conditions associated with long hydroperiods are the greatest stressor across wetland types (Mitsch and Gosselink 2007) and in created wetlands (Atkinson et al. 1993, Daniels et al. 2005). These conditions are particularly harmful to vegetation where clay soil textures already limit soil drainage and aeration. Field validation is required to capture the effect of these conditions on potential tree species for wetland creation.

While most studies only address survival, and some compare average tree growth among species, relatively new methods exist which allow tracking of individual trees across years (Peet et al. 1998, Bailey et al. 2007). In the proposed study we intend to apply their techniques to help refine our understanding of the response for various species and planting materials to conditions in the Field study and strengthen the comparison with our Mesocosm study.

Classification of Piedmont Forest Woody Vegetation

Braun (1950) classified the Piedmont forests of Virginia as Oak-Pine (Figure 1). She described the bottomland forests of the Piedmont as having sandy soils dominated by river birch, black willow, cottonwood (*Populus deltoides*), sycamore, and sweet gum along the stream sides, and the wet flats by sweet gum, willow oak, winged elm (*Ulmus rubra*), red maple (*Acer rubrum*), tulip poplar (*Liriodendron tulipifera*), green ash (*Fraxinus pennsylvanica*), and (hackberry) *Celtis laevigata* and water oak to the south. American beech (*Fagus grandifolia*) was common on northern slopes that "…raise more or less abruptly above the bottomland…." (Braun 1950). Dyer (2006) revisited Braun's work and has reclassified the Virginia portion of the Piedmont as the Oak-Pine section of the Southern mixed system (Figure 2). He also includes the western most edges of the Piedmont as part of the Mesophytic region.

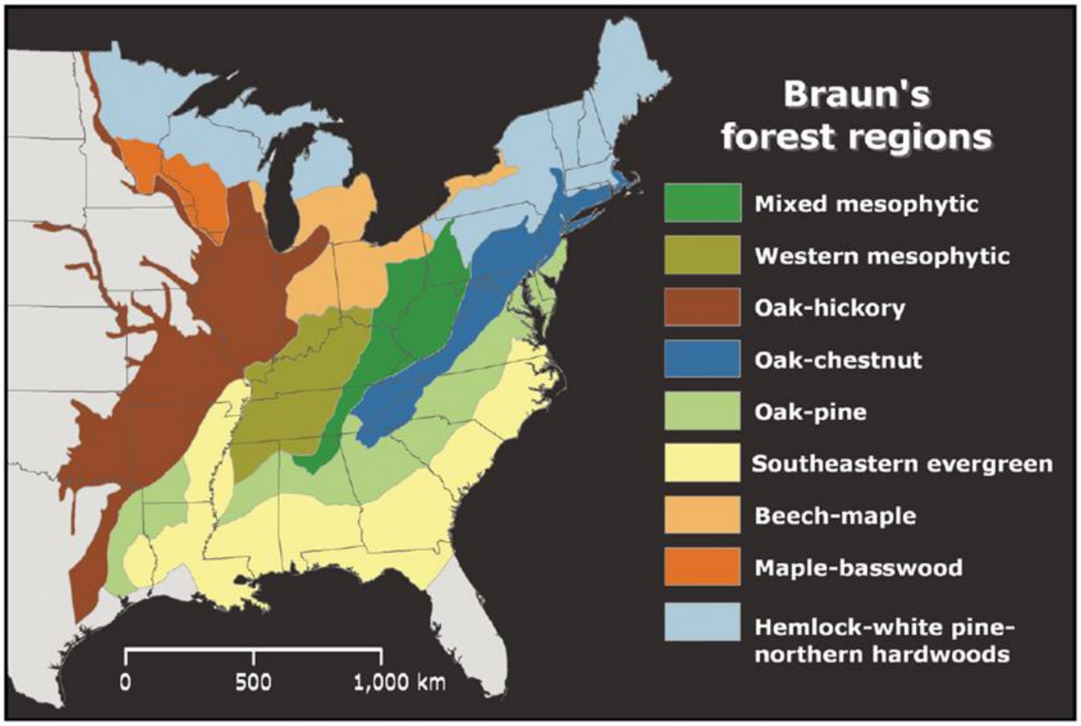


Figure 1. Nine regions described by Braun (1950), representing original forests of eastern North America.

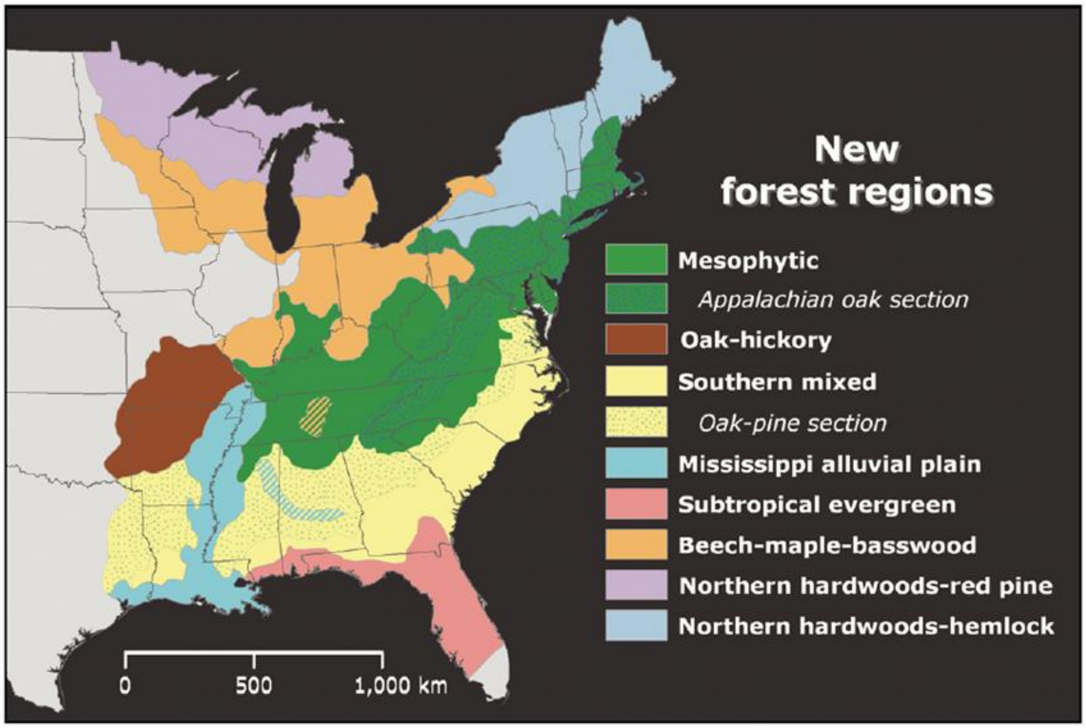


Figure 2. Regions derived from contemporary forest data. The cross-hatching in the Nashville Basin and the black belt region indicates inclusions in the larger forest regions—areas with affinities to the noncontiguous region with the same color as the cross-hatching (from Dyer 2006).

Tasks

In order to complete the objectives and goals of this study we are engaged in four major tasks:

1. Complete a thorough literature review: This is a detailed determination of various planting options. We, and our past students, have already completed a good deal of this work prior to preparing the proposal. The principal portion of this task fell in the first 13 months of the project. The review will, however, be updated yearly throughout the life of the study. This work will be overseen by the PIs and conducted primarily by the VIMS doctoral student.

2. Design and implement Mesocosm study: This phase of the project is being directed by Dr. Perry with assistance from Dr. Atkinson, and implemented and monitored by the VIMS Ph.D. student, Herman Hudson. Work on this task was focused primarily in the first six months of the project and continues with tri-annual morphometric collection.

3. Locate, implement and monitor the Field study: Dr. Atkinson worked with WSSI, MBRT, and other groups in the Piedmont region to designate field sites. Plantings on the chosen sites were coordinated with the Mesocosm study and planting occurred in March 2009.

4. Synthesis of results: As well as the quarterly reports, in December of the 1st, 2nd, 4th and 6th year of the study we prepare annual reports that present the data and results from each of the studies, led by Dr. Perry with input from Dr. Atkinson. For the 3rd (this year), 5th, and 7th year of the study the annual report will be comprehensive and include the analysis of survival and growth rate and functional development of individual woody species of both the Mesocosm and Field study. The project's graduate students are heavily involved in all report preparation.

Methods

Mesocosm Study Design

This phase of the project was directed by Dr. Perry with assistance from Dr. Atkinson and implemented and monitored by VIMS. The Mesocosm site is located at the New Kent Forestry Center, in Providence Forge, VA (Appendix 1). The site was divided into three cells each having dimensions of 48.8m x 144m (160ft x 300ft). Soil of the Ideal and Saturated cells were disked and tilled in February 2009 prior to planting. The Flooded cell was excavated to a depth of 1m (3.1ft) to an existing clay layer. An on-site irrigation system capable of producing a minimum of 2.54cm (1in) of irrigation per hour was established in each cell. The pump inlet is located approximately 8km (5mi) upriver above the Rock-a-hoc Dam (Lanexa, VA; therefore non-tidal) and irrigation water was drawn from the Chickahominy River. The hydrology of the three cells is manipulated to include an Ideal treatment (a minimum 2.5cm (1in) irrigation or rain per week), a Saturated treatment (kept saturated at a minimum of 90% of the growing season in the root-zone (10cm) of the plantings and irrigated as needed), and a Flooded treatment (inundated above the root collar at least 90% of year). To exclude herbaceous competition as a confounding variable, the Ideal and Saturated cells are mowed approximately every ten days and herbicide (Roundup®) was applied at the rate specified on the package label around the base of each planting.

Field Study Design

Drs. Atkinson and Perry worked with Wetland Studies and Solutions, Inc., Mitigation Bank Research Team, and other groups in the Piedmont Province to designate field sites. Three (3) Piedmont constructed wetland field sites were chosen for the study (Appendix 1) and are comprised of the three phases (Designated as Phase I, II, and III) of the Loudoun County Wetland and Stream Mitigation Bank (LCWSB) that were designed and installed by Wetland Studies and Solutions, Inc. Each site has a clay base soil (the most common planting medium), two to three years of documented hydrologic data and relatively uniform topography (see Appendix 2 for detailed construction methods). The overall hydrology is driven principally by rainfall such that typical Piedmont Province created wetland conditions are represented. Finally, the sites have an annual hydroperiod in which the saturated zone is at the soil surface for the majority of growing season.

The original study concept contained three study sites with 525 trees planted at each site for a total of 1575 individuals. High priority was given to consistency in homogeneity of site conditions and the three Phases of the LCWSB were deemed suitable based on this criterion. Upon further inspection at the three phases of the LCWSB, the balanced arrangement was not possible due to the configuration and conditions found on the three sites so extra plots were added at Phase III.

At Phase I, four plots each containing three subplots with 21 plantings (a complete subsample) in each subplot (252 saplings) were installed in late winter 2009. An unrelated study conducted in the two northern sections of the phase eliminated them as a possibility for this study. The size of the remaining area was not adequate to fit 525 saplings with the 8’ spacing requirement. The first post-construction growing season at Phase I was 2007 and the study saplings were planted before the beginning of the third growing season (2009).

At Phase II, four plots each containing three subplots with 21 saplings in each subplot (252 saplings) were installed in late winter 2009. The majority of the site, when surveyed, exhibited hydrologic conditions that were somewhat wetter than the other two phases. Hydrology in a small portion was similar to the other phases but could not fit 525 saplings with the 8’ spacing requirement. The first growing season at Phase II was 2008 and study saplings were planted before the beginning of the second growing season (2009).

At Phase III, 17 plots each containing three or four subplots with 21 saplings in each subplot (1092 saplings) were installed in late winter 2009. This phase exhibited fairly uniform hydrology and vegetation and had enough space to fit the remainder of the saplings with the required 8’ spacing. The first growing season at Phase III was 2008 and the study saplings were planted before the beginning of the second growing season (2009).

The saplings planted in the Field study were from the same stock as the saplings planted in the Mesocosm study, consisting of the same seven species and stocktypes, including 1) bare-root seedlings, 2) tubelings, and 3) 1 gal pots, which totals 21 (7 x 3) experimental units. Each site is completely replicated and randomized in each planting area such that every hydrological unit of the Mesocosm study will be represented in each plot. Planting was completed in early March 2009 in conjunction with the Mesocosm study.

Mortality and morphometric data were collected using methods modified from Bailey et al. (2007). Each sapling was mapped using an x- and y- coordinate grid system to aid with location in the future. Survival and growth of each planting (height, canopy cover and basal diameter as in the Mesocosm study) were recorded in a one-week period in mid-April of 2009 and in August of all subsequent years. In addition to direct comparisons with the Mesocosm results, analysis of the data collected from the Field study was conducted independently to identify which species and stocktype performed the best in these field conditions.

Planting Material

Based upon our review of the literature, practical experience in the field, and availability of planting material, we compared the following stocktypes: 1) bare-root seedlings, 2) tubelings, and 3) 1 gallon pots. We used seven woody tree species common to the forested wetlands of the Piedmont: *Betula nigra* (river birch), *Liquidambar styraciflua* (sweetgum), *Platanus occidentalis* (American sycamore), *Quercus bicolor* (swamp white oak), *Q. palustris* (pin oak), *Q. phellos* (willow oak) and *Salix nigra* (black willow). All saplings were planted in March 2009 in the Mesocosm and Field sites. Care was taken to assure that each was placed properly in the hole and covered to avoid formation of air-pockets. Saplings came from five nurseries (three in Virginia, one in North Carolina, and one in South Carolina); tubelings of three species (*P. occidentalis*, *Q. phellos*, and *S. nigra*) were two years old and had had their soil removed by the nursery prior to shipment (See Appendix 3 for list of Nurseries). This practice is uncommon and was noted in all analyses. Saplings were kept in cold storage at the New Kent Forestry Center until planted. In order to reduce the number of confounding variables, fertilizers were not applied following outplanting.

A total of 2,772 trees were planted; 44 of each species and stocktype for a total of 924 trees per cell. Trees were arranged in 22 rows per cell (42 trees per row) that were staggered. Therefore, trees were spaced 7.5 ft (2.26 m) from trees within the row and 8.39 ft (2.56 m) from trees in adjacent rows. This lead to a density of 692 stems/acre (1711 stems/ha). During the Spring of 2010, 482 new trees were purchased and planted to insure adequate sample size. Replacement trees did not necessarily come from the same nursery (See Appendix 3 for Distribution of Planted and Replanted Trees). No replanting occurred in the Field sites.

Sampling Techniques

The same sampling techniques for the survival and growth measurements were implemented at both the Mesocosm and Field sites. In the Mesocosm survival and growth were measured in April, August, and October in each of the three years. In the Field study, survival and growth were measured in April and July of the first year and August in the subsequent years. Several additional environmental variables were measured at the Mesocosm and Field study sites. At the Mesocosm site, soil physical and chemical characteristics, preliminary photosynthetic rates, and biomass were measured. At the Field study sites, the herbaceous vegetation was analyzed during the August (2012 and 2013) sampling period.

Survival

Individuals were considered “live” based on the presence of green leaves or a green vascular cambium. The latter was necessary as we noted that many trees exhibited die-back and re-growth. To check for a live cambium a small longitudinal incision scratch was made at the highest point on the stem. If brown (i.e. not alive), a second incision was made approximately one half way down the stem. If brown, a final incision was made at the base. If any of the incision showed a green cambium, the individual was considered alive.

Growth

Tree morphology (basal stem diameter at soil level, canopy diameter, and height of highest stem) was collected using methods modified from Bailey et al. (2007). Total height (H) was sampled using a standard meter stick or 5-m stadium rod, while canopy diameter (CD) and basal diameter (BD) were quantified using macro-calipers (Haglof, Inc. “Mantax Precision” Calipers) and micro-calipers (SPI 6”/.1 mm Poly Dial Calipers), respectively. Canopy diameter was measured in three angles at the maximum visual diameter to determine the average canopy diameter. Basal diameter (BD) was measured at the base of the stem (trunk) or, if buttressing present (defined as base diameter > 10% larger than bole above swelling), at the base and also just above the visual top of stem base swelling (hypertrophy). The latter measure was necessary since buttressing often accompanies trees growing in flooded conditions (Cronk and Fennessy 2001). If there were multiple stems for a planting, basal diameter of all stems was measured. In order to calculate a single basal area for each tree, the basal area of each stem was calculated and then basal areas were summed. Die back and re-growth (coppicing and re-sprouting) were common in many of the Mesocosm plantings (often leading to negative growth rates) and were noted during sampling.

Percent change per year was calculated to eliminate any size related growth differences when comparing species and stocktypes (Hunt 1990). In addition this calculation allows for comparison with mitigation bank woody growth rate success criteria.

Soil Properties

The soil physical and chemical properties were analyzed during the summer of 2010 (n=18) and summer 2013 (n=132) at the Mesocosm study site. The properties that were measured included bulk density, percent carbon, percent nitrogen and percent phosphorus. Soil grain size analysis is currently being completed with the summer 2013 soil samples.

Biomass

A subsample of the trees planted in 2009 and trees replanted in 2010 was removed from the Mesocosm in the fall and winter of 2010. The above and belowground portions of the trees were separated and placed in individual paper bags. All trees were solar dried on-site until constant weight was obtained. The trees were weighed at the end of the summer in 2011.

Results

Environmental Conditions

In order to determine the differences between the Mesocosm and Field studies as well as the differences among the Mesocosm cells, several physical and chemical characteristics of the environment were measured.

Hydrology

In order to quantify the hydrologic conditions within the Mesocosm four WaterScout SM100 Soil Moisture Sensors (Spectrum Technologies, Inc) were installed on July 7, 2013. The probes were installed at 10cm and data was recorded on a WatchDog 1400 Micro Station. The four probes were installed as a preliminary attempt to quantify the hydrologic condition because previous attempts with shallow groundwater monitoring wells and peizometers were unsuccessful. The probes are located in the middle of row 20 in the Saturated cell and in row 1 of the Flooded cell. The probes are ~20ft from the data logger. Extension cords were tested on two of the probes but did not function correctly. The probes were calibrated with soil from the site and measure the percent volumetric water content which represents the percent of the total volume of soil that is occupied by water.

The data suggest that the percent volumetric water content can increase dramatically after rainfall or irrigation and then slowly decrease within the Saturated cell (Figure 3). Also, two of the probes (Saturated B and F) did not respond to the hydrologic input near 11-1-2013 as Saturated M did. The probe in the Flooded cell did not fluctuate as dramatically, possibly as a result of the perched water table.

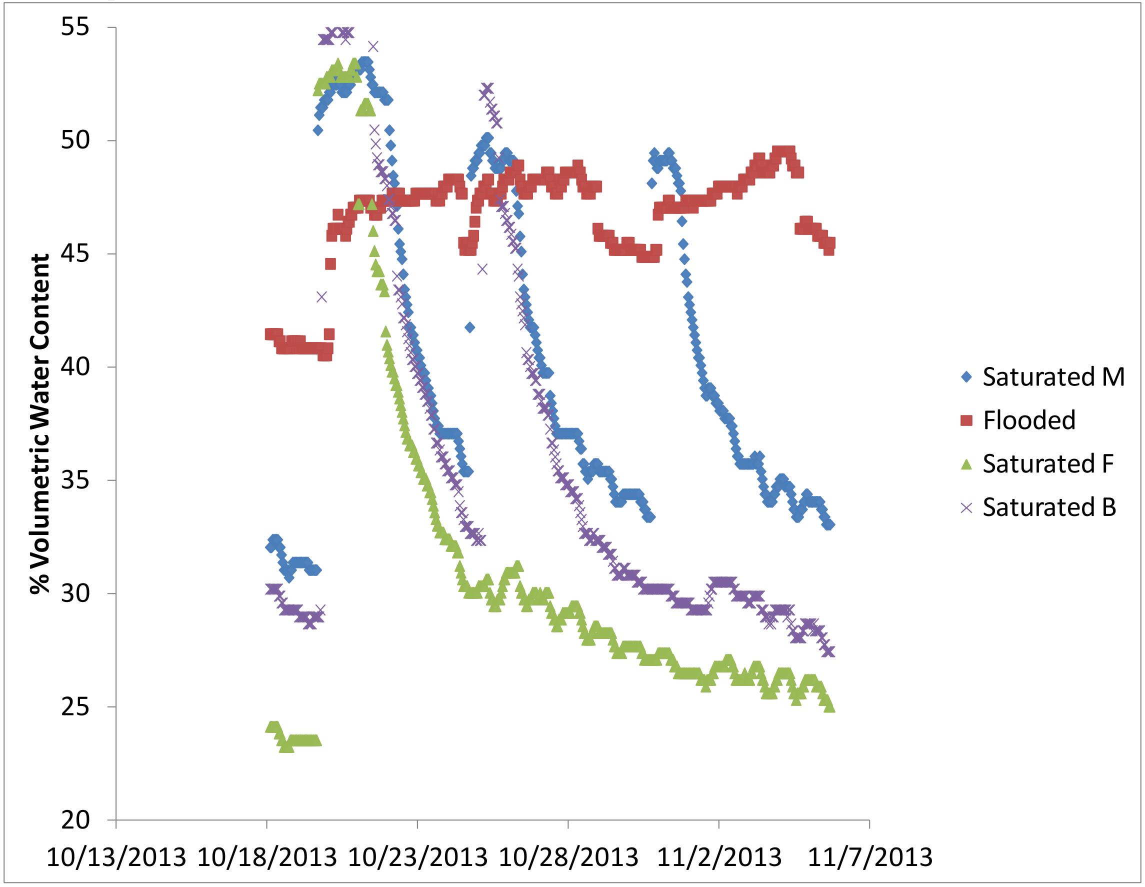


Figure 3. Percent volumetric water content from four soil moisture test probes.

These results suggest that there are differences in the hydrologic treatments among the cells and that the hydrology is not uniform throughout the Saturated cell. Based on these results and the ease of use, additional probes will be installed at the Mesocosm to measure the soil volumetric water content.

Soil

Soil analysis suggests that there may be differences in the soil physical and chemical properties among the cells and that those properties may have changed since 2010. The bulk density is slightly higher in the Flooded cell than the Saturated and Ideal cells and has decreased in the Ideal and Saturated cells since 2010 (Figure 4). The percent phosphorus (Figure 5), carbon (Figure 6), and nitrogen (Figure 7) are lower in the Flooded cell compared to the Saturated and Ideal cells. The percent carbon has decreased in the Ideal cell and increased in the Saturated and Flooded cells (Figure 6). The percent nitrogen has decreased in all of the cells (Figure 7).

The lower nutrient concentrations and high bulk density in the Flooded cell is most likely the result of topsoil removal during construction which was accomplished using heavy machinery. The changes in soil characteristics may indicate ecosystem development. The increase in carbon in the Saturated cell may indicate deceased decomposition rates and buildup of organic matter, while the decrease in carbon in the Ideal cell may indicate increased microbial respiration and decomposition enhanced by the tree roots.

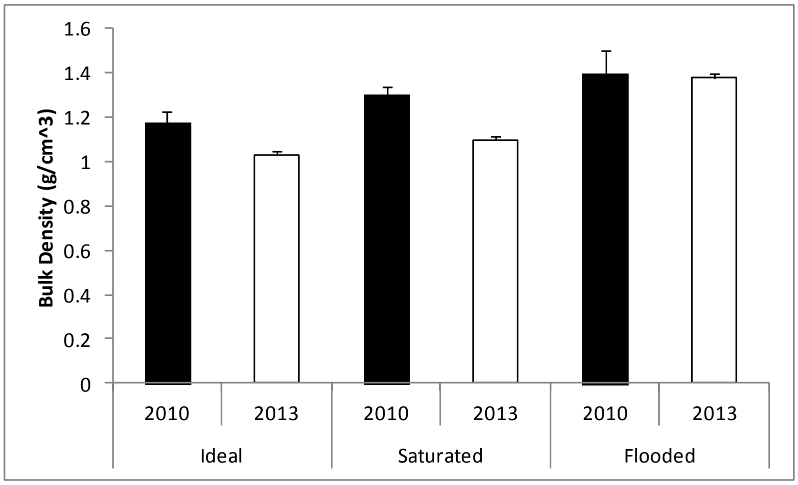


Figure 4. Bulk density within each cell from 2010 and 2013. Error bars represent standard error.

In addition to variability among the cells, the soil characteristics exhibit spatial variability within each cell (Figure 8). For example, the soil percent nitrogen within the Ideal cell ranges from 0.14 % to 0.23 % from east to west.

The differences in soil characteristics within and among cell may have impacts on tree growth and survival in conjunction with the hydrologic treatment. Therefore, future analysis of survival and growth will seek to model the effect of both variables simultaneously.

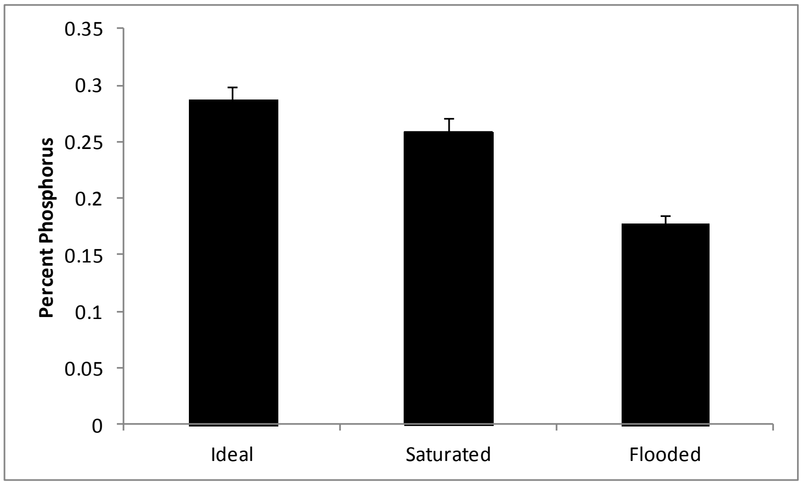


Figure 5. Percent phosphorus within each cell in 2013. Samples were processes incorrectly in 2010. Error bars represent standard error.

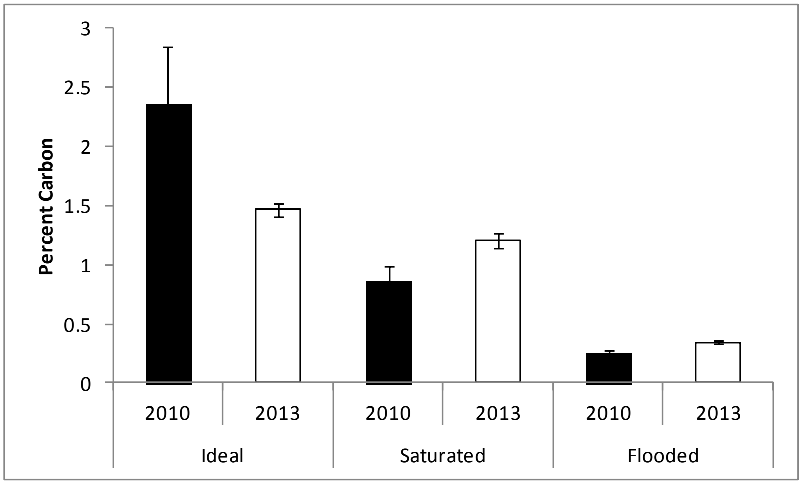


Figure 6. Percent carbon within each cell from 2010 and 2013. Error bars represent standard error.

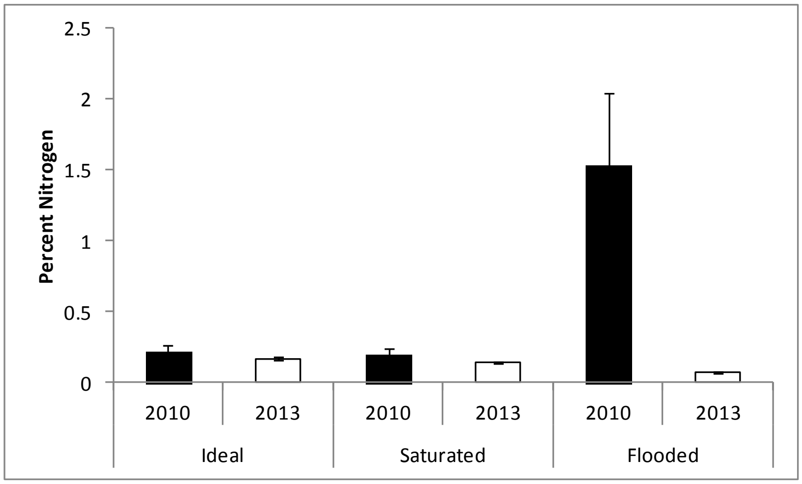


Figure 7. Percent nitrogen within each cell from 2010 and 2013. 2010 Measurement from 2010 in the Flooded cell most likely resulted from contamination.

Figure 8. Location of planted trees and position of soil samples. Colors represent interpolated concentration of soil percent nitrogen.

Objective 1

The factors used to determine the most appropriate woody vegetation for planting in created wetlands were; percent survival, percent change in height per year, canopy diameter, and cost per ha. These factors were calculated for each species/stocktype combination in the Mesocosm and Field portions of this study. Species/stocktype combinations were ranked based on the combination of the above factors.

Appropriate woody vegetation can also be determined by comparison to the ecological performance standards required for forested wetland compensation sites. The USACE Norfolk District and the VADEQ (2004) recommend 200 to 400 stems/acre as a minimum woody stem count for compensatory sites. However, many projects have been required to have >400 stems/acre (990 stems/ha) (Mike Rolband, pers. comm.). The VADEQ also requires a woody height growth rate of 10% per year for mitigation banks (VADEQ 2010). However, this requirement has not been adopted by most projects (Mike Rolband, pers. comm.). Additionally both of these ecological performance standards are required until the canopy reaches 30% cover or greater. Results will focus on meeting these three recommendations and will focus on the 21 species/stocktype combinations that were planted in the Mesocosm and Field sites.

Survival

In order to meet the required woody stem density, trees could be planted on 8ft centers, which would yield 681 stems/acre. However, to ensure the required >400 stems/acre (990 stems/ha), the percent survival of planted trees would need to remain above 58.8%. Therefore, only those species/stocktype combinations exhibiting greater than 58.8% survival qualify as appropriate selections for planting.

After five years the species that were grown in the gallon containers had greater than the required 58.8% survival in the Ideal cell and Saturated cell (Table 1). In the Flooded cell only six species/stocktype combinations had greater than 58.8% survival; the *B. nigra* gallon and tubeling, the *L. styraciflua* gallon, and all three stocktypes of *S. nigra.* In the Field study gallon stocktypes of all species except *P. occidentalis,* and *L. styraciflua* had greater than 58.8% survival. None of the species that were planted as bare root stocktype had greater than 58.8% survival after three years in the Field study. After five years the highest survival rate was the gallon *B. nigra, Q. palustris* and *Q. bicolor* in the Ideal cell (100% survival), *L. styraciflua* and *Q. bicolor* gallon in the Saturated cell (100%), and *S. nigra* gallon in the Flooded cell (95.1%). In the Field study, *Q. palustris* gallon had had the greatest percent survival (73.3%) after five years.

In year five several species/stocktype combinations dropped below 58.8% survival. In the Ideal cell *P. occidentalis* bare root, in the Saturated cell *B. nigra* bare root and *Q. phellos* tubeling NO SOIL and in the Field study, *L. styraciflua* bare root and *Q. palustris* tubeling all dropped below 58.8% survival. This suggests that there is continued mortality long after planting.

To facilitate interpretation of the following result sections, the number of living trees is presented in Table 2.

Table 1. Percent survival for 2009, 2010, 2011, 2012 and 2013. Red represents <58.8% survival. Yellow represents species stocktype combinations that fell below 58.8% survival in year five.

		Ideal					Saturated					Flooded					Field				
Species	**Stocktype**	**2009 % Survival**	**2010 % Survival**	**2011 % Survival**	**2012 % Survival**	**2013 % Survival**	**2009 % Survival**	**2010 % Survival**	**2011 % Survival**	**2012 % Survival**	**2013 % Survival**	**2009 % Survival**	**2010 % Survival**	**2011 % Survival**	**2012 % Survival**	**2013 % Survival**	**2009 % Survival**	**2010 % Survival**	**2011 % Survival**	**2012 % Survival**	**2013 % Survival**
Betula nigra	Bare root	48.9	42.2	42.2	42.2	42.2	71.7	60.9	60.9	60.9	58.7	66.1	50.0	30.4	19.6	19.6	89.5	48.7	46.1	46.1	39.5
Betula nigra	Gallon	100.0	100.0	100.0	100.0	100.0	97.4	97.4	97.4	97.4	97.4	100.0	100.0	90.0	87.5	80.0	97.4	75.0	69.7	62.7	66.2
Betula nigra	Tubeling	35.3	32.4	32.4	32.4	32.4	82.9	77.1	77.1	74.3	71.4	94.4	91.7	75.0	75.0	72.2	89.5	50.0	48.7	47.4	46.1
Liquidambar styraciflua	Bare root	75.0	72.7	72.7	70.5	70.5	87.5	80.0	75.0	72.5	72.5	89.5	76.3	39.5	31.6	34.2	84.2	59.2	48.7	43.4	31.6
Liquidambar styraciflua	Gallon	100.0	92.9	95.2	95.2	95.2	100.0	100.0	100.0	100.0	100.0	100.0	95.0	82.5	75.0	77.5	94.7	77.6	68.4	66.2	46.8
Liquidambar styraciflua	Tubeling	25.6	20.5	20.5	20.5	20.5	62.8	48.8	41.9	39.5	39.5	91.9	81.1	48.6	45.9	45.9	62.3	22.1	22.1	18.7	12.0
Platanus occidentalis	Bare root	63.0	60.9	60.9	58.7	58.7	50.0	50.0	50.0	50.0	50.0	40.0	28.6	0.0	0.0	0.0	69.7	35.5	30.3	30.3	21.1
Platanus occidentalis	Gallon	92.9	85.7	85.7	85.7	83.3	97.6	97.6	97.6	97.6	95.1	82.5	47.5	27.5	17.5	20.0	71.1	46.1	38.2	34.7	30.7
Platanus occidentalis	Tubeling NO SOIL	97.0	97.0	97.0	97.0	97.0	76.5	76.5	70.6	67.6	67.6	44.4	22.2	5.6	5.6	5.6	90.8	60.5	50.0	48.7	42.1
Quercus bicolor	Bare root	92.0	88.0	82.0	82.0	80.0	100.0	97.6	97.6	92.9	92.9	95.3	60.5	30.2	18.6	20.9	89.5	63.2	57.9	53.3	44.0
Quercus bicolor	Gallon	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	87.2	61.5	35.9	35.9	98.7	96.1	94.7	92.1	75.0
Quercus bicolor	Tubeling	74.0	60.0	54.0	52.0	48.0	81.8	79.5	75.0	68.2	68.2	80.4	34.8	10.9	4.3	8.7	90.7	78.7	74.7	67.1	60.5
Quercus palustris	Bare root	87.5	79.2	75.0	72.9	72.9	97.4	92.3	87.2	79.5	82.1	88.2	52.9	7.8	3.9	5.9	96.1	67.1	55.3	53.9	50.0
Quercus palustris	Gallon	100.0	100.0	100.0	100.0	100.0	100.0	100.0	95.3	95.3	95.3	97.7	74.4	30.2	16.3	25.6	97.4	89.5	85.5	84.2	76.3
Quercus palustris	Tubeling	55.9	44.1	32.4	29.4	29.4	74.3	60.0	54.3	54.3	51.4	75.0	22.2	8.3	2.8	2.8	86.8	72.4	65.8	61.5	56.4
Quercus phellos	Bare root	75.0	66.1	53.6	51.8	50.0	79.7	75.0	65.6	62.5	59.4	70.6	35.3	13.2	4.4	5.9	86.8	36.8	31.6	22.1	11.7
Quercus phellos	Gallon	100.0	97.4	92.1	89.5	89.5	100.0	97.3	94.6	94.6	94.6	100.0	67.5	40.0	27.5	40.0	92.1	84.2	80.3	77.9	70.1
Quercus phellos	Tubeling NO SOIL	63.0	40.7	40.7	37.0	37.0	70.8	64.6	62.5	56.3	56.3	50.0	10.7	0.0	0.0	0.0	67.1	18.4	7.9	6.6	7.9
Salix nigra	Bare root	26.5	8.8	5.9	5.9	5.9	69.6	45.7	34.8	34.8	32.6	90.7	90.7	86.0	88.4	86.0	77.6	38.2	34.2	30.2	28.9
Salix nigra	Gallon	97.5	97.5	92.5	92.5	92.5	95.1	95.1	92.7	92.7	90.2	95.1	95.1	85.4	95.1	95.1	98.7	72.4	71.1	68.4	67.1
Salix nigra	Tubeling NO SOIL	59.1	52.3	40.9	40.9	38.6	75.0	51.8	39.3	33.9	32.1	92.3	84.6	84.6	82.1	76.9	89.5	64.5	60.5	48.3	49.3

Table 2. Number of trees planted and number of living trees for each year. Trees removed for biomass are not included.

		Ideal						Saturated						Flooded					
Species	**Stocktype**	**Planted**	**2009 N**	**2010 N**	**2011 N**	**2012 N**	**2013 N**	**Planted**	**2009 N**	**2010 N**	**2011 N**	**2012 N**	**2013 N**	**Planted**	**2009 N**	**2010 N**	**2011 N**	**2012 N**	**2013 N**
Betula nigra	Bare root	45	22	19	19	19	19	46	33	28	28	28	27	56	37	28	17	11	11
Betula nigra	Gallon	39	39	39	39	39	39	39	38	38	38	38	38	40	40	40	36	35	33
Betula nigra	Tubeling	34	12	11	11	11	11	35	29	27	27	26	25	36	34	33	27	27	26
Liquidambar styraciflua	Bare root	44	33	32	32	31	31	40	35	32	30	29	28	38	34	29	15	12	13
Liquidambar styraciflua	Gallon	42	42	39	40	40	40	39	39	39	39	39	39	40	40	38	33	30	31
Liquidambar styraciflua	Tubeling	39	10	8	8	8	8	43	27	21	18	17	17	37	34	30	18	17	17
Platanus occidentalis	Bare root	46	29	28	28	27	27	6	3	3	3	3	3	35	14	10	0	0	0
Platanus occidentalis	Gallon	42	39	36	36	35	35	41	40	40	40	40	39	40	33	19	11	7	8
Platanus occidentalis	Tubeling NO SOIL	33	32	32	32	31	32	34	26	26	24	23	23	18	8	4	1	1	1
Quercus bicolor	Bare root	50	46	44	41	41	40	42	42	41	41	39	39	43	41	26	13	8	9
Quercus bicolor	Gallon	37	37	37	37	37	37	39	39	39	39	39	39	39	39	34	24	14	14
Quercus bicolor	Tubeling	50	37	30	27	26	24	44	36	35	33	30	29	46	37	16	5	2	4
Quercus palustris	Bare root	48	42	38	36	35	35	39	38	36	34	31	32	51	45	27	4	2	3
Quercus palustris	Gallon	39	39	39	39	39	39	43	43	43	41	41	41	43	42	32	13	7	11
Quercus palustris	Tubeling	34	19	15	11	10	10	35	26	21	19	19	18	36	27	8	3	1	1
Quercus phellos	Bare root	56	42	37	30	29	28	64	51	48	42	40	38	68	48	24	9	3	4
Quercus phellos	Gallon	38	38	37	35	34	34	37	37	36	35	35	35	40	40	27	16	11	16
Quercus phellos	Tubeling NO SOIL	27	17	11	11	10	10	48	34	31	30	27	27	28	12	3	0	0	0
Salix nigra	Bare root	34	9	3	2	2	2	46	32	21	16	16	15	43	39	39	37	38	37
Salix nigra	Gallon	40	39	39	37	37	37	41	39	39	38	38	37	41	39	38	35	39	39
Salix nigra	Tubeling NO SOIL	44	26	23	18	18	16	56	42	29	22	19	18	39	36	33	33	32	30

Height Growth

There were three species/stocktype combinations that did not meet the required >10% height increase in 2009 in the Ideal cell; however, in 2010, 2011, 2012 and 2013 all species/stocktype achieved the required >10% increase in height (Table 3). In the Saturated cell ten species/stocktype did not meet percent height increase 2009 and four did not meet it in 2010. All 21 species/stocktype combinations had >10% increase in height in the Saturated cell in 2011, 2012 and 2013. In the Flooded cell 8 species/stocktype combinations had less than 10% increase in height in 2009, 15 in 2010, 18 in 2011, 9 in 2012. In the Field sites 18 species/stocktype did not meet the >10% requirement in 2009, while in 2010 it declined to nine species/stocktype below the >10% increase requirement and only two in 2011. In 2012 all species/stocktypes met the required >10% increase in height in the Field study. In 2013 however, 7 species stocktype combinations did not meet the requirement.

The general trend of height growth in the Ideal cell is similar among the species/stocktype combination, there is an initial increase (higher for the gallon stocktype) followed by a decrease to ~35% in 2013. In the Saturated cell there appears to be an initial increase in height growth for the gallon stocktype followed by a decrease in 2010 and then an increase in 2011 to ~95%. There is a decrease following 2011 to an average height growth rate of ~50% (which is greater than the growth rate in the Ideal cell). In the Field study there appears to be die back in the first two years followed by an increase in height growth rate in 2011 and 2012 followed by a decline to an average of 14% increase in height in 2013 (See Appendix 4 for percent change in height graphs).

Table 3. Average percent change in height per year for 2009, 2010, 2011, 2012, 2013. Percentage represents change over one year. Red indicates dieback and orange indicates <10% increase. NA represents combinations that had 0% survival.

		Ideal					Saturated					Flooded					Field				
Species	**Stocktype**	**2009 % Height**	**2010 % Height**	**2011 % Height**	**2012 % Height**	**2013 % Height**	**2009 % Height**	**2010 % Height**	**2011 % Height**	**2012 % Height**	**2013 % Height**	**2009 % Height**	**2010 % Height**	**2011 % Height**	**2012 % Height**	**2013 % Height**	**2009 % Height**	**2010 % Height**	**2011 % Height**	**2012 % Height**	**2013 % Height**
Betula nigra	Bare root	48.7	173.3	132.9	49.4	31.3	-4.5	84.2	126.1	60.7	57.7	23.9	6.6	-30.8	97.9	49.1	-9.5	35.4	24.7	43.8	50.1
Betula nigra	Gallon	582.9	85.5	60.4	46.8	31.8	972.7	34.3	61.7	87.1	35.2	35.8	5.0	17.0	-8.6	24.0	-4.0	-12.3	3.3	15.9	23.8
Betula nigra	Tubeling	111.7	129.5	144.3	62.9	51.0	123.5	105.1	122.5	59.5	64.4	24.3	13.3	-10.5	9.9	37.1	9.4	25.2	31.0	30.6	43.5
Liquidambar styraciflua	Bare root	108.3	163.8	104.5	46.7	40.7	-44.5	74.3	115.8	81.1	60.5	-7.5	5.5	-3.7	5.6	18.1	-5.9	-15.1	44.6	44.8	28.8
Liquidambar styraciflua	Gallon	533.8	87.2	70.9	39.3	34.5	635.3	54.8	58.9	57.7	52.6	73.7	-1.1	-4.5	1.8	-11.6	5.5	-16.1	52.3	25.4	23.2
Liquidambar styraciflua	Tubeling	-67.7	216.1	123.0	56.3	37.8	-161.1	98.9	143.6	56.4	72.1	103.0	19.5	3.2	19.6	20.8	22.7	75.8	46.4	35.2	81.3
Platanus occidentalis	Bare root	176.2	317.5	128.2	51.7	37.7	8.9	94.1	184.5	101.4	91.0	-56.6	-25.6	NA	NA	NA	-24.1	26.7	37.6	38.7	22.9
Platanus occidentalis	Gallon	804.8	106.2	90.2	45.3	35.0	647.8	5.6	66.0	22.5	49.1	-6.6	-30.0	-22.3	-4.9	7.8	-13.6	-20.8	66.4	27.8	11.9
Platanus occidentalis	Tubeling NO SOIL	232.6	243.1	92.6	44.7	32.7	107.5	61.1	180.5	65.7	52.5	-15.5	10.2	0.0	-53.6	12.5	-19.0	5.9	47.5	46.4	31.8
Quercus bicolor	Bare root	140.0	16.7	45.8	42.4	36.4	267.7	16.6	55.2	38.1	33.9	23.0	-17.1	-36.9	20.5	11.6	2.5	-17.2	13.7	30.2	29.2
Quercus bicolor	Gallon	89.1	87.3	55.6	48.9	35.9	62.8	32.0	69.1	28.3	54.4	62.7	-3.3	-3.1	-2.8	-8.6	10.5	6.5	19.1	17.6	11.6
Quercus bicolor	Tubeling	-122.4	32.2	76.7	68.2	38.6	-150.0	11.8	81.4	45.5	47.2	27.4	-11.1	-15.9	15.0	-1.0	4.2	54.9	37.5	24.6	25.9
Quercus palustris	Bare root	113.8	38.8	64.5	64.9	34.0	-60.7	13.8	95.0	47.8	33.4	20.1	-31.1	-5.3	11.0	10.2	-1.2	-13.3	36.3	38.8	22.4
Quercus palustris	Gallon	479.9	22.7	37.9	47.8	35.2	547.1	3.9	33.2	27.6	31.8	18.9	-8.3	-44.7	3.5	-22.1	3.6	11.8	1.2	26.6	9.18
Quercus palustris	Tubeling	-122.3	72.9	93.4	45.1	17.9	-174.1	56.0	70.5	78.2	28.4	-0.2	4.5	-12.9	8.0	9.1	-25.7	73.9	53.3	24.1	17.8
Quercus phellos	Bare root	42.5	32.6	73.6	69.7	44.2	-13.7	47.8	91.8	58.8	42.5	-9.5	-25.0	-4.7	67.2	10.0	-15.7	-39.3	30.2	33.8	42.9
Quercus phellos	Gallon	769.3	41.2	40.7	32.6	71.7	888.2	7.7	32.9	25.8	77.0	12.3	-9.0	-15.2	-16.1	-13.7	11.6	4.8	29.6	10.6	13.4
Quercus phellos	Tubeling NO SOIL	100.7	98.9	57.4	73.1	42.2	-74.0	67.3	81.5	59.7	48.2	-43.8	-39.4	NA	NA	NA	-31.8	-55.6	117.0	37.4	17
Salix nigra	Bare root	-55.9	137.2	80.3	104.2	58.7	50.9	154.9	135.7	73.1	39.0	12.8	71.8	21.4	25.5	23.9	0.7	60.8	37.0	34.3	13.3
Salix nigra	Gallon	794.9	22.5	48.1	43.6	30.5	517.9	0.3	89.0	45.6	28.2	26.4	1.5	-3.7	2.8	11.2	7.1	2.4	21.0	29.2	14.9
Salix nigra	Tubeling NO SOIL	327.0	98.9	125.0	62.1	34.8	46.4	34.6	112.1	77.3	55.5	-2.1	62.4	38.3	5.8	31.4	0.6	21.9	27.1	37.8	19.7

Canopy Closure

The stem density and height growth ecological performance standards are no longer required when the canopy coverage of trees greater than 100 cm tall exceeds 30% (788,031.5 cm^2) of the standard 30ft-radius circle plot (2,626,772.6 cm^2) (USACE Norfolk District 2004, VADEQ 2010a). The minimum required stem density (400 stems/acre or 990 stems/ha) corresponds to 26 trees in a plot of this size. Assuming all trees were alive, 30% of the plot would be covered if the canopy diameter (CD) of each tree was >200 cm. Based on the 7.5ft x 8.39ft planting arrangement of trees in this study (692 stems/acre), 30% of the plot would be covered if the canopy diameter of each tree was >150 cm. Using the canopy diameter from this study, the approximate time of 30% canopy closure was determined for each species/stocktype combination in each cell of the Mesocosm and in the Field study.

None of the species/stocktype combinations exceeded 150 cm in diameter in the Flooded cell or in the Field site over five years (Table 4). However, in the Ideal cell all of the species and stocktype combinations exceeded 150 cm in canopy diameter by 2013. In 2013, *Q. bicolor* gallon and *Q. phellos* bare root exceeded the requirement.

Table 4. Average Canopy Diameter (CD) of all 21 species/stocktype combinations for 2009-2013 in the Mesocosm and Field sites that had heights greater than 100 cm. Green cells represent combinations that obtained 30% canopy closure (>150 cm) at the planting density in this study. Yellow cells represent combinations that obtained 30% canopy closure in year four. Blanks represent combinations that had no trees greater than 100cm.

		Ideal					**Saturated**					**Flooded**					**Field**				
Species	**Stocktype**	**2009 CD (cm)**	**2010 CD (cm)**	**2011 CD (cm)**	**2012 CD (cm)**	**2013 CD (cm)**	**2009 CD (cm)**	**2010 CD (cm)**	**2011 CD (cm)**	**2012 CD (cm)**	**2013 CD (cm)**	**2009 CD (cm)**	**2010 CD (cm)**	**2011 CD (cm)**	**2012 CD (cm)**	**2013 CD (cm)**	**2009 CD (cm)**	**2010 CD (cm)**	**2011 CD (cm)**	**2012 CD (cm)**	**2013 CD (cm)**
Betula nigra	Bare root	65.7	122.3	288.9	392.7	461.7		73.2	167.3	259.2	369.2				105.3	93.7	75.2		42.1	46.9	57.5
Betula nigra	Gallon		190.0	360.4	487.2	625.3	56.3	112.2	247.7	356.1	456.3	59.2	57.4	51.3	83.7	90.1	75.9	77.0	61.7	80.9	99.9
Betula nigra	Tubeling		126.6	230.3	364.1	443.5		72.3	173.0	283.9	397.3			33.0	114.0	74.9		47.3	42.8	59.9	80.7
Liquidambar styraciflua	Bare root		104.8	179.2	255.4	341.4		71.8	107.7	172.4	255.3					84.3			37.0	35.4	43.0
Liquidambar styraciflua	Gallon	55.6	115.8	183.9	255.1	318.8	34.8	68.8	139.6	203.0	265.7	45.0	45.6	43.4	40.1	48.5	28.8	38.1	46.0	52.2	69.6
Liquidambar styraciflua	Tubeling		114.8	161.3	214.8	293.6		62.3	108.5	158.8	241.6					40.3				47.2	73.7
Platanus occidentalis	Bare root		109.1	257.4	377.8	524.3		43.7	66.8	150.2	227.9								25.0	45.0	48.3
Platanus occidentalis	Gallon	50.7	125.8	224.9	318.7	409.2	31.2	60.1	137.1	196.6	264.8	30.7	26.1	18.8		57.3	32.8	40.3	39.6	56.9	74.3
Platanus occidentalis	Tubeling NO SOIL	39.0	131.3	291.6	415.4	559.2		48.8	116.0	225.8	353.2							19.0	26.6	33.7	50.0
Quercus bicolor	Bare root		80.8	125.3	160.9	188.0			114.2	105.4	135.3					87.7				58.3	59.1
Quercus bicolor	Gallon		75.7	124.0	150.7	203.4		54.8	97.0	107.2	156.1				70.3	118.3	45.5	46.7	47.7	55.4	68.4
Quercus bicolor	Tubeling		69.3	107.4	139.7	174.7			78.1	87.1	109.8							17.0			47.5
Quercus palustris	Bare root		70.3	114.2	158.6	201.5			84.6	110.0	143.0									46.0	
Quercus palustris	Gallon	65.0	97.1	139.9	195.3	235.2	65.6	76.3	109.8	162.4	180.9	66.8	62.0	70.3	82.2	116.7	48.3	49.6	49.5	52.5	59.6
Quercus palustris	Tubeling			87.7	122.3	159.0			88.7	100.4	117.2										40.6
Quercus phellos	Bare root		97.0	131.7	143.2	181.1		27.0	95.2	121.4	160.7	76.2	73.3		64.9						22.0
Quercus phellos	Gallon	69.9	103.9	174.0	224.9	266.9	64.7	88.1	150.3	190.2	231.5	68.0	69.5	61.2		88.6	49.1	57.3	47.0	55.1	77.5
Quercus phellos	Tubeling NO SOIL	68.8	99.0	139.9	167.1	183.4			105.2	115.6	135.6										
Salix nigra	Bare root		97.3	291.7	235.5	281.7		83.1	228.0	320.3	363.7		74.8	80.0	79.0	104.2	14.0	54.1	60.4	71.2	90.9
Salix nigra	Gallon	69.8	166.7	297.1	337.3	362.6	44.9	91.2	201.3	290.4	327.4	55.2	98.2	112.2	97.1	116.3	49.8	66.8	82.6	113.9	149.0
Salix nigra	Tubeling NO SOIL	39.3	133.4	206.1	292.9	349.2		67.3	208.6	252.7	336.9		79.6	95.4	78.1	94.1	35.4	49.9	58.2	85.7	105.6

Flowering

In Spring 2012 it was noted that several species flowered, therefore in spring 2013 we recorded the number of trees that were flowering (Table 5). *S. nigra* and *B. nigra* have the highest percentage of trees that flowered and the gallon stocktype typically had higher percent flowering than the other stocktypes. More species/stocktype combinations were flowering in the Ideal cell but the Saturated cell had a higher average percent flowering. There were very few trees in the Flooded cell that flowered in 2013. The primary successional species typically flowered more than the oak species.

Table 5. The percent flowering for each species/stocktype combination within each cell in spring 2013. NA represents combinations for which there were no live trees.

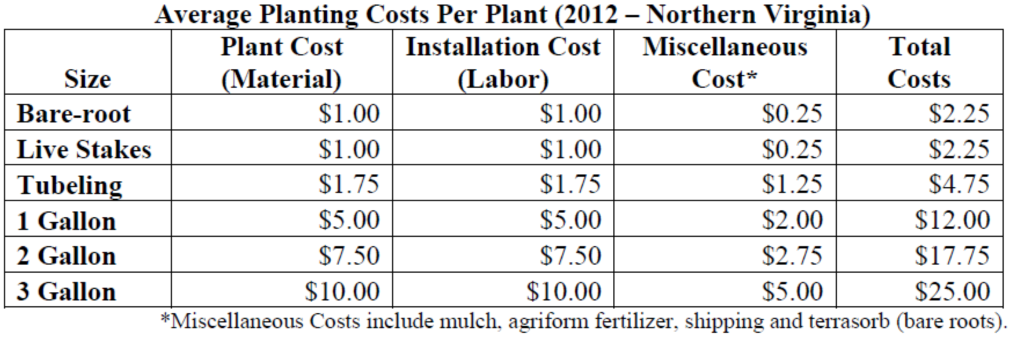
Species	Stocktype	% Flowering Ideal	% Flowering Saturated	% Flowering Flooded
Betula nigra	Bare root	26.3	11.1	0
Betula nigra	Gallon	51.3	76.3	3.0
Betula nigra	Tubeling	9.1	36.0	0
Liquidambar styraciflua	Bare root	22.6	0	0
Liquidambar styraciflua	Gallon	10.0	10.3	0
Liquidambar styraciflua	Tubeling	12.5	0	0
Platanus occidentalis	Bare root	3.7	0	NA
Platanus occidentalis	Gallon	11.4	2.6	0
Platanus occidentalis	Tubeling NO SOIL	12.5	4.3	0
Quercus bicolor	Bare root	14.6	10.5	0
Quercus bicolor	Gallon	10.8	23.1	0
Quercus bicolor	Tubeling	11.1	3.4	0
Quercus palustris	Bare root	0	0	0
Quercus palustris	Gallon	0	0	0
Quercus palustris	Tubeling	0	5.3	0
Quercus phellos	Bare root	0	2.6	25.0
Quercus phellos	Gallon	2.9	0	0
Quercus phellos	Tubeling NO SOIL	0	0	NA
Salix nigra	Bare root	50.0	86.7	18.4
Salix nigra	Gallon	73.0	78.4	7.5
Salix nigra	Tubeling NO SOIL	66.7	83.3	3.1

Economic Analysis

In order to determine the cost required to insure adequate stem density, the plant material cost, installation cost, and miscellaneous costs (Table 6) were combined with the percent survival after five years (Table 7).

The results from this analysis suggest that while the gallon stocktype generally exhibit increased survival, it is more cost effective to plant additional bare root stocktypes. Rarely is the tubeling stocktype the most economic choice based on survival and total cost.

Table 6. Average planting costs per tree for 2012 in Northern Virginia. Provided by Wetland Studies and Solutions, Inc.

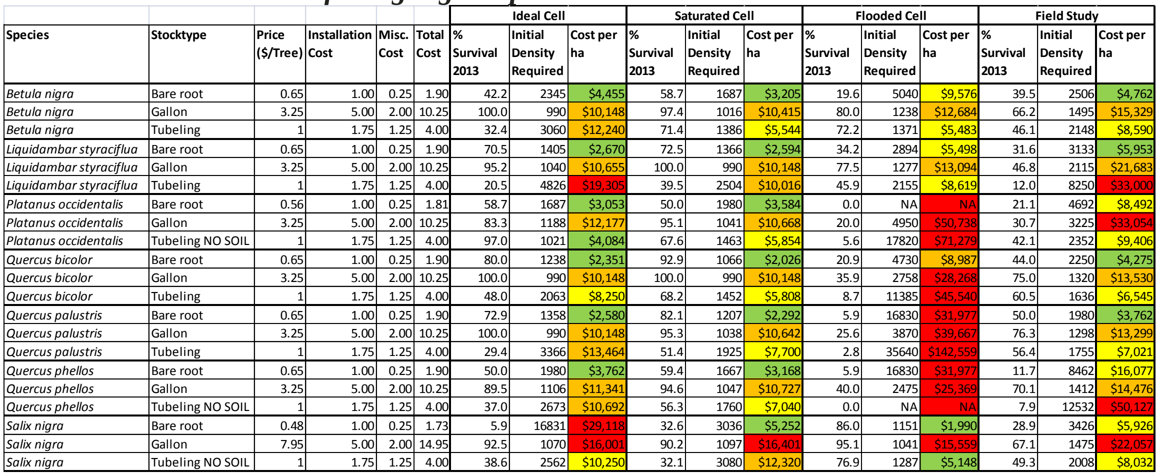


Average Planting Costs Per Plant (2012 – Northern Virginia)

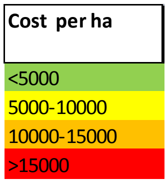
Size	Plant Cost (Material)	Installation Cost (Labor)	Miscellaneous Cost*	Total Costs
Bare-root	$1.00	$1.00	$0.25	$2.25
Live Stakes	$1.00	$1.00	$0.25	$2.25
Tubeling	$1.75	$1.75	$1.25	$4.75
1 Gallon	$5.00	$5.00	$2.00	$12.00
2 Gallon	$7.50	$7.50	$2.75	$17.75
3 Gallon	$10.00	$10.00	$5.00	$25.00

*Miscellaneous Costs include mulch, agriform fertilizer, shipping and terrasorb (bare roots).

Table 7. Percent survival represents the survival four years following outplanting. The initial density required represents the initial stem density (stems/acre) required for ensuring >400 stems/acre (990 stems/ha) based on the percent survival of a given species/stocktype combination. The cost per ha is the dollar amount required to plant at the initial density for these particular species/stocktype combinations. See table below for highlight representation.



						Ideal Cell			Saturated Cell			Flooded Cell			Field Study		
Species	Stocktype	Price ($/Tree)	Installation Cost	Misc. Cost	Total Cost	% Survival 2013	Initial Density Required	Cost per ha	% Survival 2013	Initial Density Required	Cost per ha	% Survival 2013	Initial Density Required	Cost per ha	% Survival 2013	Initial Density Required	Cost per ha
Betula nigra	Bare root	0.65	1.00	0.25	1.90	42.2	2345	$4,455	58.7	1687	$3,205	19.6	5040	$9,576	39.5	2506	$4,762
Betula nigra	Gallon	3.25	5.00	2.00	10.25	100.0	990	$10,148	97.4	1016	$10,415	80.0	1238	$12,684	66.2	1495	$15,329
Betula nigra	Tubeling	1	1.75	1.25	4.00	32.4	3060	$12,240	71.4	1386	$5,544	72.2	1371	$5,483	46.1	2148	$8,590
Liquidambar styraciflua	Bare root	0.65	1.00	0.25	1.90	70.5	1405	$2,670	72.5	1366	$2,594	34.2	2894	$5,498	31.6	3133	$5,953
Liquidambar styraciflua	Gallon	3.25	5.00	2.00	10.25	95.2	1040	$10,655	100.0	990	$10,148	77.5	1277	$13,094	46.8	2115	$21,683
Liquidambar styraciflua	Tubeling	1	1.75	1.25	4.00	20.5	4826	$19,305	39.5	2504	$10,016	45.9	2155	$8,619	12.0	8250	$33,000
Platanus occidentalis	Bare root	0.56	1.00	0.25	1.81	58.7	1687	$3,053	50.0	1980	$3,584	0.0	NA	NA	21.1	4692	$8,492
Platanus occidentalis	Gallon	3.25	5.00	2.00	10.25	83.3	1188	$12,177	95.1	1041	$10,668	20.0	4950	$50,738	30.7	3225	$33,054
Platanus occidentalis	Tubeling NO SOIL	1	1.75	1.25	4.00	97.0	1021	$4,084	67.6	1463	$5,854	5.6	17820	$71,279	42.1	2352	$9,406
Quercus bicolor	Bare root	0.65	1.00	0.25	1.90	80.0	1238	$2,351	92.9	1066	$2,026	20.9	4730	$8,987	44.0	2250	$4,275
Quercus bicolor	Gallon	3.25	5.00	2.00	10.25	100.0	990	$10,148	100.0	990	$10,148	35.9	2758	$28,268	75.0	1320	$13,530
Quercus bicolor	Tubeling	1	1.75	1.25	4.00	48.0	2063	$8,250	68.2	1452	$5,808	8.7	11385	$45,540	60.5	1636	$6,545
Quercus palustris	Bare root	0.65	1.00	0.25	1.90	72.9	1358	$2,580	82.1	1207	$2,292	5.9	16830	$31,977	50.0	1980	$3,762
Quercus palustris	Gallon	3.25	5.00	2.00	10.25	100.0	990	$10,148	95.3	1038	$10,642	25.6	3870	$39,667	76.3	1298	$13,299
Quercus palustris	Tubeling	1	1.75	1.25	4.00	29.4	3366	$13,464	51.4	1925	$7,700	2.8	35640	$142,559	56.4	1755	$7,021
Quercus phellos	Bare root	0.65	1.00	0.25	1.90	50.0	1980	$3,762	59.4	1667	$3,168	5.9	16830	$31,977	11.7	8462	$16,077
Quercus phellos	Gallon	3.25	5.00	2.00	10.25	89.5	1106	$11,341	94.6	1047	$10,727	40.0	2475	$25,369	70.1	1412	$14,476
Quercus phellos	Tubeling NO SOIL	1	1.75	1.25	4.00	37.0	2673	$10,692	56.3	1760	$7,040	0.0	NA	NA	7.9	12532	$50,127
Salix nigra	Bare root	0.48	1.00	0.25	1.73	5.9	16831	$29,118	32.6	3036	$5,252	86.0	1151	$1,990	28.9	3426	$5,926
Salix nigra	Gallon	7.95	5.00	2.00	14.95	92.5	1070	$16,001	90.2	1097	$16,401	95.1	1041	$15,559	67.1	1475	$22,057
Salix nigra	Tubeling NO SOIL	1	1.75	1.25	4.00	38.6	2562	$10,250	32.1	3080	$12,320	76.9	1287	$5,148	49.3	2008	$8,032



Cost per ha
🟩 <5000
🟨 5000-10000
🟧 10000-15000
🟥 >15000

Species/Stocktype Ranking

Here we present one strategy for addressing Objective 1 in which we assemble 63 ranked lists of the 21 species/stocktype combinations. This approach uses data from the Mesocosm and Field studies for all five years (Table 8). Note that this method necessarily conceals some variation in the data and treats all years and variables equally. When five years of both Mesocosm and Field studies are combined, the optimum species/stocktype combination was *B. nigra* gallon. The top five combinations are gallon stocktype, while the *P. occidentalis* gallon did very poorly in the Flooded and Field. In the top ten species only three are oak species.

Table 8. The ranking of all species and stocktype in the Mesocosm, Field and Overall.

Species	Stocktype	Overall Rank	Ideal Rank	Saturated Rank	Flooded Rank	Field Rank
Betula nigra	Gallon	1	1	1	2	5
Salix nigra	Gallon	2	6	7	4	1
Liquidambar styraciflua	Gallon	3	5	2	5	6
Quercus phellos	Gallon	4	7	4	7	3
Quercus bicolor	Gallon	5	8	6	8	2
Betula nigra	Tubeling	6	12	3	6	9
Salix nigra	Tubeling NO SOIL	7	13	17	3	8
Quercus palustris	Gallon	8	9	10	12	4
Salix nigra	Bare root	9	20	13	1	12
Betula nigra	Bare root	10	11	9	10	11
Liquidambar styraciflua	Bare root	11	10	8	13	16
Platanus occidentalis	Tubeling NO SOIL	12	2	11	19	10
Platanus occidentalis	Gallon	13	4	5	15	18
Quercus bicolor	Bare root	14	15	12	11	14
Liquidambar styraciflua	Tubeling	15	17	19	9	17
Quercus palustris	Bare root	16	14	14	17	13
Quercus bicolor	Tubeling	17	18	20	16	7
Platanus occidentalis	Bare root	18	3	15	21	19
Quercus phellos	Bare root	19	16	16	14	20
Quercus palustris	Tubeling	20	21	21	18	15
Quercus phellos	Tubeling NO SOIL	21	19	18	20	21

Objective 2

The second objective of this study is to determine the appropriate vegetative measures that will identify whether wetland functions are occurring. To address objective 2, four goals were described;

1) Relate tree structure (morphometrics) to above and belowground biomass (Dimensional analysis).
2) Relate tree structure to Net Ecosystem Exchange (NEE).
3) Determine vegetation similarity of created forested wetlands and reference sites.
4) Determine the role of volunteer woody species.

Goals three and four were addressed by Sean Charles' (in press) and Herman Hudson's (2010) Master theses. Goal two could not be addressed by this study because the use of the TPS-2 was unsuccessful due to the large size of the trees. The TPS-2 and other similar devices (LICOR 6400) use a very small chamber that encapsulates small portions of individual leaves and is therefore impractical for making whole plant or ecosystem based estimates of gas exchange.

Dimensional Analysis

Goal one was addressed in this study by destructively harvesting a subsample of the trees planted in 2009 (n=189) and trees planted in 2010 (n=162) in the mesocosm. Sampling occurred after leaf senescence and leaf biomass was not measured. Therefore, biomass refers only to roots, shoots and branches. Linear regression was be used to determine the relationship between total biomass (above and belowground) and all three morphological measurements (basal diameter, height and canopy diameter). The biomass and morphological parameters was natural log transformed to homogenize variance. The biomass of all remaining living trees will be calculated based on morphological measurements and used to determine leafless woody productivity.

Preliminary results suggest that the three morphological measurements (Table 9) are able to describe the variation in biomass (Table 10). Further analysis using Akaike information criterion (AIC) will be used to determine if a single morphological measurement would be adequate to describe the variation in biomass and if there are differences in allometry among the cells. Additionally, further biomass sampling may be needed to increase the range of each measurement.

Table 9. Range of measured morphological characteristics

Species	n	Basal Area Range (cm^2)	Height Range (cm)	Canopy Diameter Range (cm)
Betula nigra	45	0.13 - 42.46	35 - 355	15 - 328.25
Liquidambar styraciflua	51	0.03 - 32.98	4 - 295	5.75 - 228.5
Platanus occidentalis	54	0.11 - 54.24	4 - 285	4.5 - 201.25
Quercus bicolor	46	0.08 - 33.47	9 - 112	8 - 100.5
Quercus palustris	52	0.08 - 5.15	14 - 182	7.25 - 138.75
Quercus phellos	50	0.09 - 9.35	19 - 295	7.25 - 177.5
Salix nigra	52	0.02 - 17.09	8 - 183	3.75 - 197.75

Table 10. Results of linear regression utilizing all three morphometric measurements.

Species	α	β1ln(BA)	β2ln(H)	β3ln(CD)	r2
All Species	0.3132	0.54	0.38	0.59	0.848
Betula nigra	-2.4697	0.37	0.56	1.06	0.925
Liquidambar styraciflua	-0.592	0.49	0.71	0.52	0.875
Platanus occidentalis	0.7243	0.56	0.27	0.63	0.892
Quercus bicolor	-0.3186	0.31	0.44	0.80	0.734
Quercus palustris	-0.3639	0.60	0.73	0.41	0.880
Quercus phellos	-0.5716	0.50	0.69	0.46	0.883
Salix nigra	0.8805	0.29	-0.14	1.03	0.744

Discussion

The first objective of this study is to critically evaluate and improve upon the planting of woody vegetation in created forested headwater wetlands in the Piedmont Province, Virginia. The goal of this objective is to identify the most appropriate woody species and stocktype(s) that would be recommended for planting in created forested wetlands in the Piedmont Province of Virginia. The survival, growth, and satisfaction of the ecological performance standards (>58.8% survival and >10% increase in height per year or 30% canopy closure) of tree species/stocktype combinations planted in various environmental conditions were used to reach this goal. The results from this experiment suggest that the most appropriate species/stocktype combinations varies based on environmental conditions and in particular the hydrologic conditions that are present at a site have a large effect on which species/stocktype combinations may be most appropriate.

In the fifth growing season several species/stocktype combinations fell below 58.8% survival in the Saturated cell (*B. nigra* bare root and *Q. phellos* Tubeling NO SOIL) and in the Field study (*L. styraciflua* gallon and *Q. palustris* tubeling). While the survival has stabilized in the Ideal and Saturated cells, it continues to decrease in the Flooded cell and Field study suggesting that after five years hydrologic and competitive stress is still influencing the planted trees.

While in 2012 all of the species/stocktype combinations exceeded the 10% increase in height, seven combinations fell below this requirement in 2013. This suggests that growth rates can fluctuate substantially over two growing seasons even after overcoming transplant shock under the environmental conditions present in the created forested wetland. In the Flooded cell more combinations of species and stocktype exceeded the 10% growth rate than growing seasons two through three. This also suggests that given additional time, trees that survive can overcome hydrologic stress. Comparing the height growth rate over all five growing season, it appears that trees within the Saturated cell and Field study had similar patterns with a peak in growth in 2010 and 2011, while the Ideal cell had greater initial growth rates. This again suggests that it may take additional time to overcome transplant shock in stressful hydrologic conditions. The gallon stocktype typically had greater initial growth rates with may be important where herbaceous vegetation competition is expected.

The results from the canopy closure analysis suggest that primary successional species may reach 30% canopy closure earlier than the secondary successional species. Also, these results suggest that several years are required for planted trees to exceed 100 cm in height. In the Flooded and Field sites, none of the species/stocktype combinations exceeded 150 cm in canopy diameter, suggesting that hydrologic stress and/or herbaceous competition may reduce canopy growth rates. Only the *B. nigra* and *S. nigra* are approaching a canopy diameter of 150 cm in these locations.

Based on the results from the economic analysis, it appears that the bare root stocktype is the least expensive stocktype to insure adequate survival in most situations even though the initial density required is often higher than the other stocktypes.

When all five years of results are combined and the species/stocktypes are ranked with equal weighting, it appears that the gallon stocktype is preferred, however, the primary species may be planted as bare root or tubelings with moderate success. The tubeling and bare root stocktypes do not appear to be an appropriate choice for planting secondary species in created forested wetlands.

Overall, when choosing the plant material for forested wetland restoration, many factors need to be taken into consideration. Additionally the site conditions and budget of the restoration attempt should influence the decision to purchase particular species/stocktypes combinations.

The second objective of this study was to determine the appropriate vegetative measures that will identify whether wetland functions are occurring. The results from this study suggest that the three morphological measurements in combination have a strong relationship with above and belowground biomass. This suggest that the morphological measurements of the remaining trees could be used as surrogates for biomass and changes in these measurements could be used as an indicator of the level of woody primary production.

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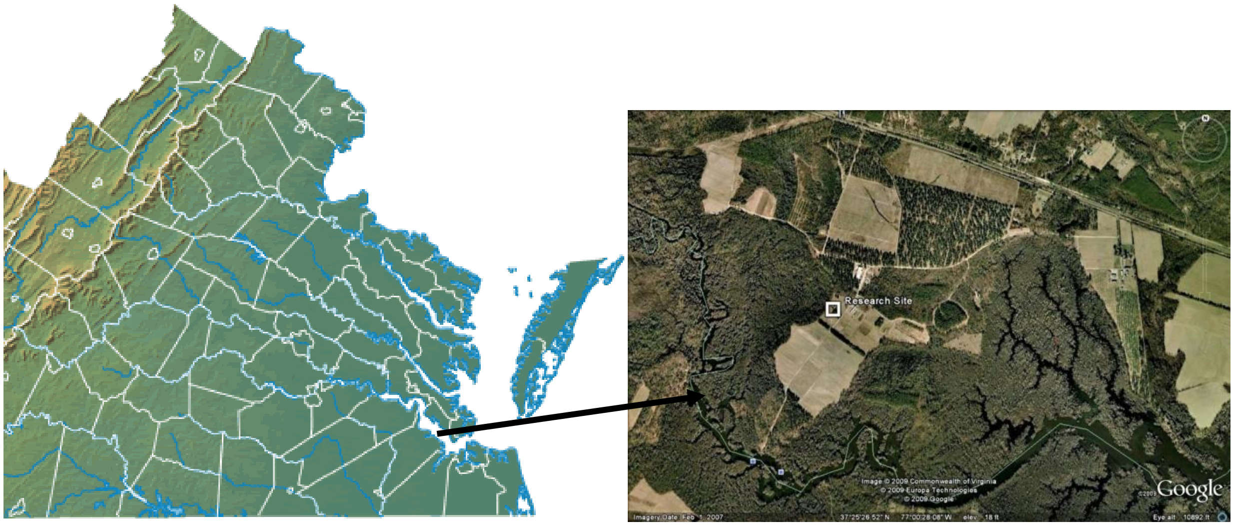
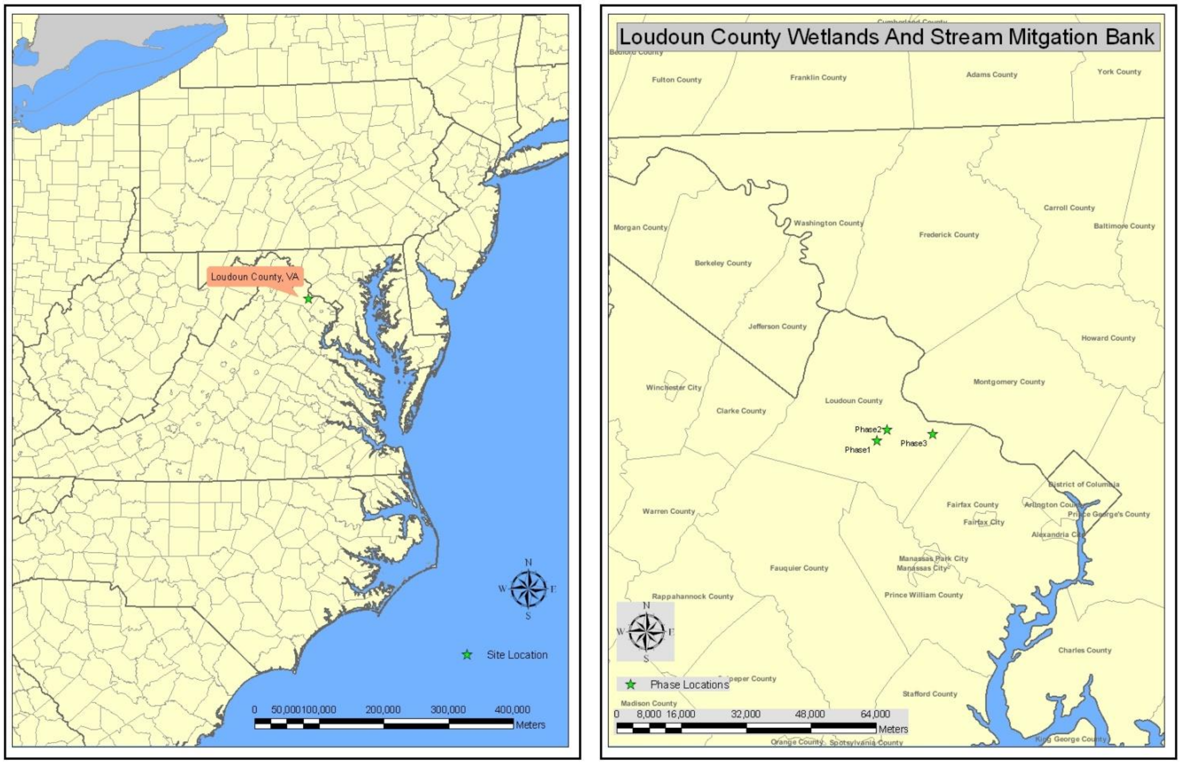
Appendix 1. Location of Mesocosm and Field Studies

Mesocosm Location



Mesocosm Site Location: New Kent County, Virginia, USA.

Field Study Site Locations



Field Study Sites Location: Loudoun County, Virginia, USA

Field Study Plot Locations

Location of Phase I, II and III plots.

Appendix 2. Field Study Construction Methods

Below are the typical construction methods of the constructed wetland areas at the Loudoun County sites. Depending on the soil fertility results, lime may also be disked into the soil.

B. Constructed Wetlands Substrate

1. The substrate of all constructed wetlands areas shall consist of a minimum of 9" of topsoil atop a 12" (or greater) thick low permeability (1 x 10-6 cm/sec or lower) subsoil layer.
2. Topsoils shall be stripped from areas proposed for grading and stockpiled for replacement upon all graded surfaces (9 inch in wetlands and 6 inch on all berms and embankments). Topsoil shall be re-spread in a loose uncompacted state in all planting areas by disking at least 6 inches deep after placement except on berms and embankments where it shall be compacted with 4 passes of a track dozer and then raked. It is expected that 4-6 passes of a disk shall be required to obtain a loose topsoil seedbed free of large (1") clumps satisfactory to WSSI.
3. After subsoil grades are achieved by either fill or excavation as needed, a low permeability subsoil substrate shall be achieved by compacting the subsoil material with a sheepsfoot roller, preferably a Caterpillar 815. Where the subsoil consists of fill, the upper 12" or more shall be placed in loose lifts not exceeding 8 inches in thickness and compacted. Where the subsoil grade is reached by excavation, the compaction effort shall be applied to the subgrade surface. Compaction shall be achieved by five passes of a sheeps foot roller with the subsoil between 3% and 7% on the wet side of the optimum moisture content. Pumping of the substrate is acceptable during this compaction process.
4. The compacted subsoil substrate shall continue ±5 feet past the outside edge of constructed wetlands areas following the rising grades proposed so that the elevation of the compacted subgrade edge is at least 0.5 feet above its elevation beneath each proposed wetlands area.
5. The referenced Soil Investigation indicates that the desired permeability can be achieved with the in-situ soils when compacted to at least eighty-five (85%) of the maximum dry density determined in accordance with ASTM D698, Standard Proctor Method between 3% and 7% on the wet side of the optimum moisture content.
6. Owner may conduct any necessary testing to assure that permeability is achieved.

C. Berms & Existing Stream Channel Fill Areas

1. Berms (small embankments 1 to 2 feet tall and 10 feet wide - except for the 4 foot wide berm between the southern wetland areas) and existing stream channel fill areas, shall be placed in 8 inch horizontal loose lifts and compacted to at least ninety-five percent (95%) of the maximum dry density determined in accordance with ASTM D698, Standard Proctor Method between 3% and 7% on the wet side of the optimum moisture content. Pumping of this material during compaction is acceptable.
2. These fill areas shall be covered with 6 inches of topsoil compacted with 4 passes of a track dozer, and then raked.
3. Berms shall be composed of cohesive materials classified as ML, CL, MH, or CH per ASTM D-2487.

Appendix 3. Distribution of Planted Trees

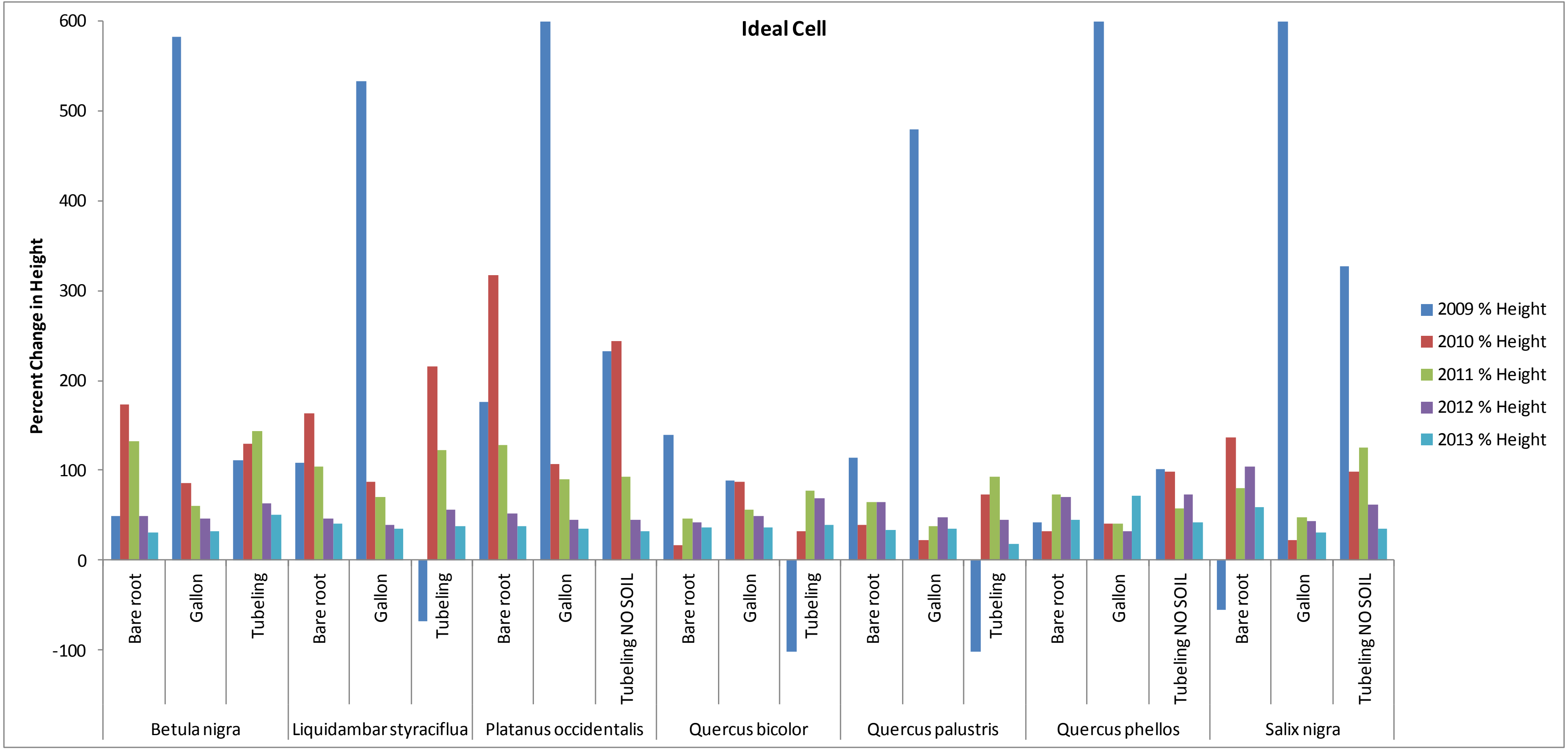
Distribution of trees planted in 2009 at the Mesocosm and Field

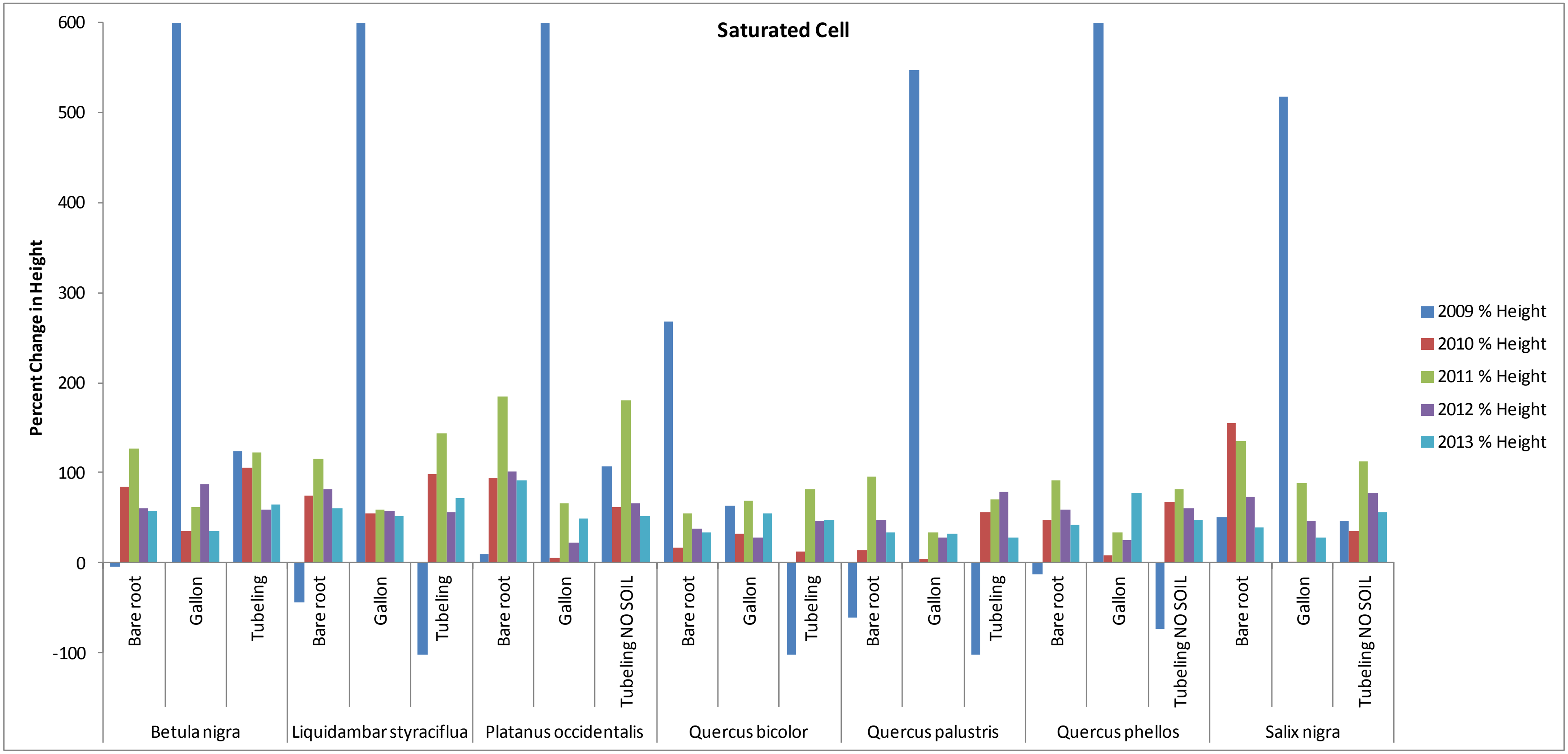
Species	Stocktype	Nursery	Location	Price ($/Tree)	Age	Ideal	Saturated	Flooded	Mesocosm Total	Phase I	Phase II	Phase III	Field Total
Betula nigra	Bare root	Native Roots Nursery	Clinton, NC	0.65		48	49	59	156	12	12	52	76
Betula nigra	Gallon	Native Roots Nursery	Clinton, NC	3.25		42	42	43	127	12	11	52	75
Betula nigra	Tubeling	Native Roots Nursery	Clinton, NC	1		37	38	39	114	12	12	52	76
Liquidambar styraciflua	Bare root	Native Roots Nursery	Clinton, NC	0.65		47	43	41	131	12	12	52	76
Liquidambar styraciflua	Gallon	Native Roots Nursery	Clinton, NC	3.25		45	43	43	131	12	12	53	77
Liquidambar styraciflua	Tubeling	Native Roots Nursery	Clinton, NC	1		42	46	40	128	12	12	51	75
Platanus occidentalis	Bare root	Warren County Nursery	McMinnville, TN	0.56		49	9	38	96	12	12	52	76
Platanus occidentalis	Gallon	Native Roots Nursery	Clinton, NC	3.25		45	44	43	132	12	12	51	75
Platanus occidentalis	Tubeling NO SOIL	Against the Wind Nursery	Atlantic, VA	1	2	36	37	21	94	12	12	52	76
Quercus bicolor	Bare root	Native Roots Nursery	Clinton, NC	0.65		53	46	46	145	12	12	51	75
Quercus bicolor	Gallon	Native Roots Nursery	Clinton, NC	3.25		40	42	42	124	12	13	51	76
Quercus bicolor	Tubeling	Native Roots Nursery	Clinton, NC	1		53	47	49	149	12	12	52	76
Quercus palustris	Bare root	Native Roots Nursery	Clinton, NC	0.65		51	42	55	148	12	12	52	76
Quercus palustris	Gallon	Native Roots Nursery	Clinton, NC	3.25		42	46	47	135	12	12	52	76
Quercus palustris	Tubeling	Native Roots Nursery	Clinton, NC	1		37	38	39	114	12	13	53	78
Quercus phellos	Bare root	Native Roots Nursery	Clinton, NC	0.65		59	69	72	200	12	12	53	77
Quercus phellos	Gallon	Native Roots Nursery	Clinton, NC	3.25		41	40	43	124	12	12	53	77
Quercus phellos	Tubeling NO SOIL	Against the Wind Nursery	Atlantic, VA	1	2	30	51	31	112	12	12	52	76
Salix nigra	Bare root	Warren County Nursery	McMinnville, TN	0.48		37	49	46	132	12	12	52	76
Salix nigra	Gallon	Pinelands Nursery	Columbus, NJ	7.95		43	44	45	132	12	12	52	76
Salix nigra	Tubeling NO SOIL	Against the Wind Nursery	Atlantic, VA	1	2	47	59	42	148	12	11	52	75

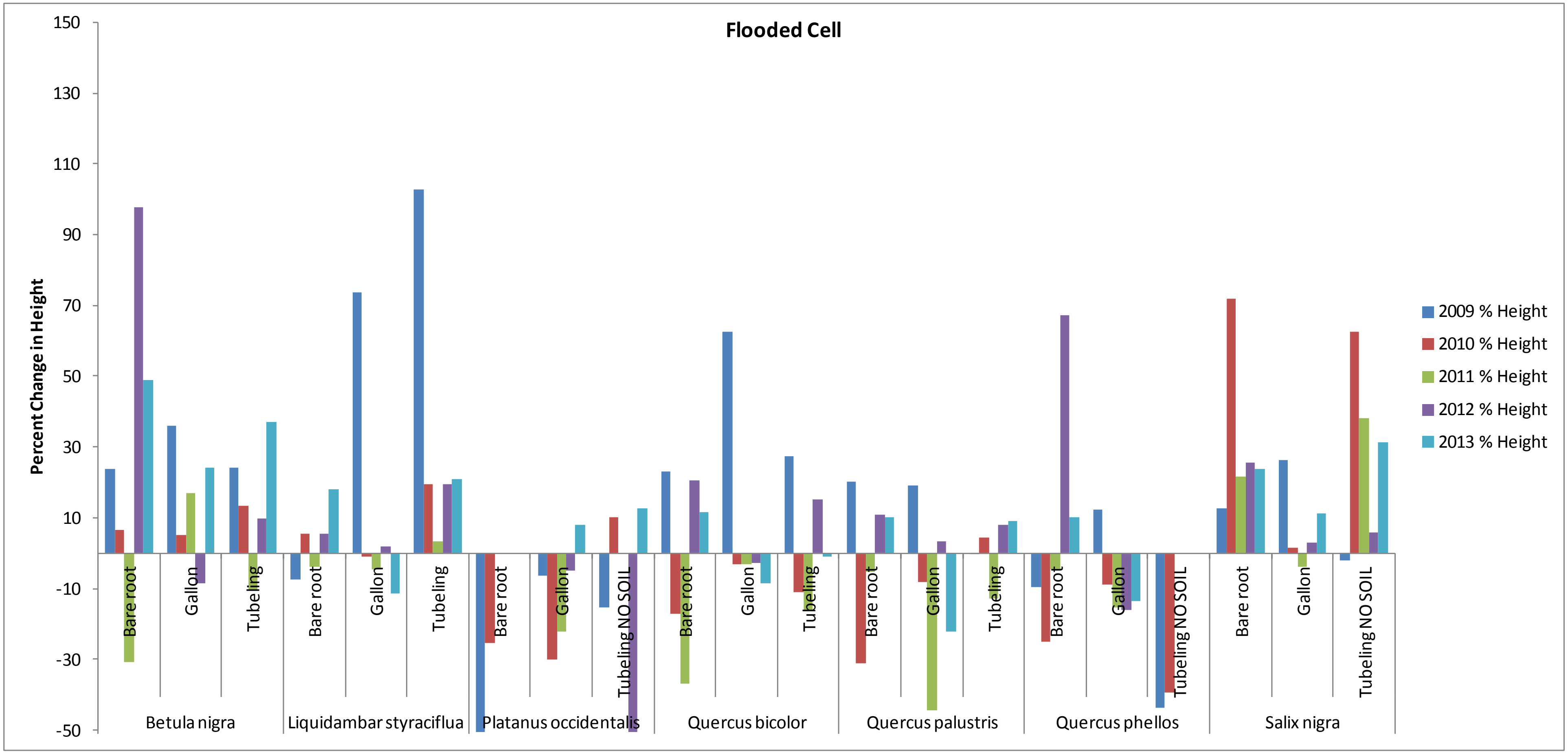
Distribution of trees planted in 2010 at the Mesocosm

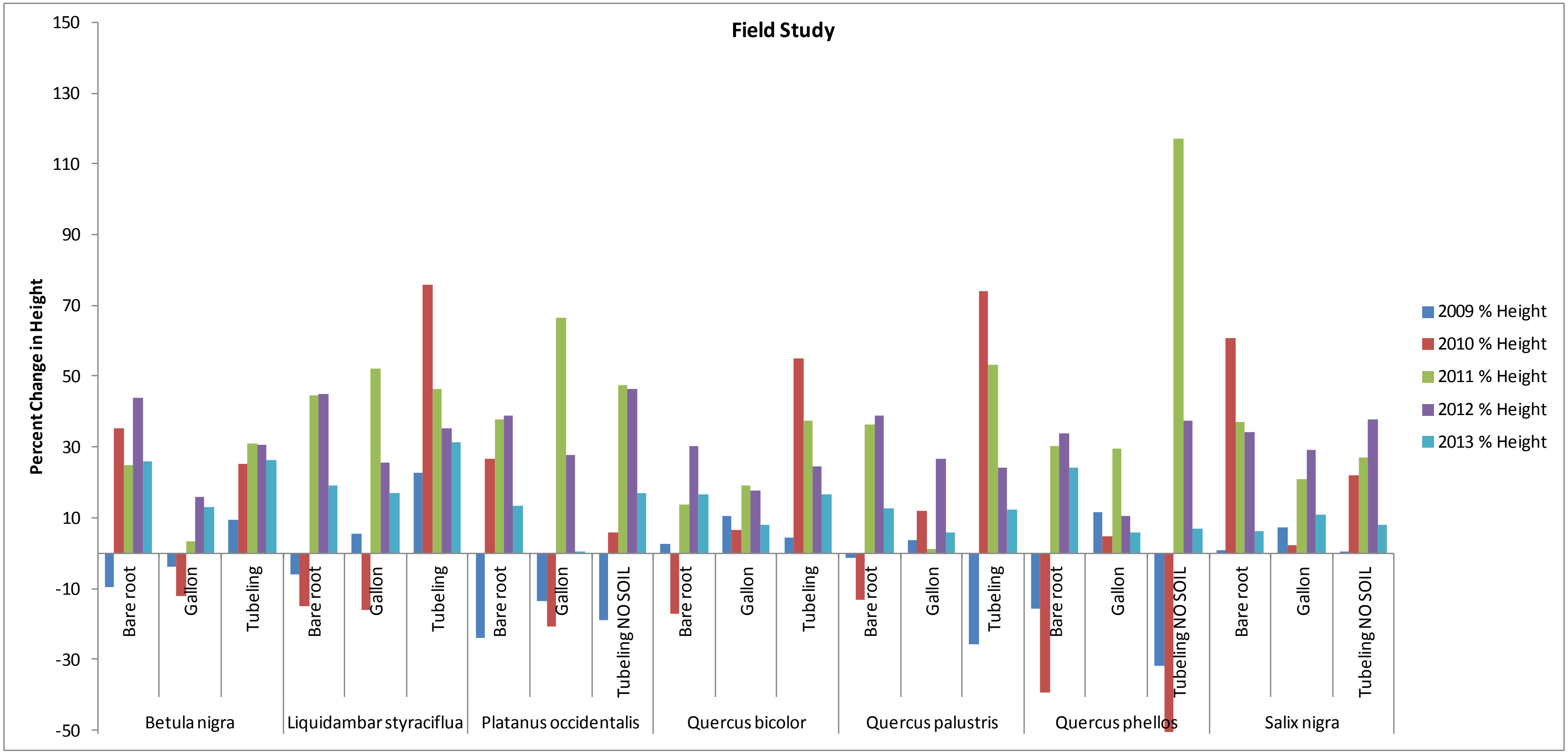
Species	Stocktype	Nursery	Location	Price ($/Tree)	Age	Ideal	Saturated	Flooded	Total Replant
Betula nigra	Bare root	Warren County Nursery	McMinnville, TN	0.32		17	7	3	27
Betula nigra	Gallon	Naturescapes Wetland Plants	Suffolk, VA	5		2	2	3	7
Betula nigra	Tubeling	Pinelands Nursery	Columbus, NJ	1.1	1	25	10	4	39
Liquidambar styraciflua	Bare root	Warren County Nursery	McMinnville, TN	0.4		10	6	5	21
Liquidambar styraciflua	Gallon	Pinelands Nursery	Columbus, NJ	5.75	2	4	3	3	10
Liquidambar styraciflua	Tubeling	Pinelands Nursery	Columbus, NJ	1.1	1	20	12	3	35
Platanus occidentalis	Bare root	Warren County Nursery	McMinnville, TN	0.5		11	30	20	61
Platanus occidentalis	Gallon	Naturescapes Wetland Plants	Suffolk, VA	5		3	3	7	13
Platanus occidentalis	Tubeling	Pinelands Nursery	Columbus, NJ	1.1		8	11	22	41
Quercus bicolor	Bare root	Warren County Nursery	McMinnville, TN	0.6		3	4	3	10
Quercus bicolor	Gallon	Naturescapes Wetland Plants	Suffolk, VA	5		4	3	3	10
Quercus bicolor	Tubeling	Pinelands Nursery	Columbus, NJ	1.1	1	4	0	3	7
Quercus palustris	Bare root	Warren County Nursery	McMinnville, TN	0.4		3	2	6	11
Quercus palustris	Gallon	Naturescapes Wetland Plants	Suffolk, VA	5		3	3	4	10
Quercus palustris	Tubeling	Pinelands Nursery	Columbus, NJ	1.1	1	20	13	10	43
Quercus phellos	Bare root	Warren County Nursery	McMinnville, TN	0.35		4	1	6	11
Quercus phellos	Gallon	Pinelands Nursery	Columbus, NJ	9.5		4	4	4	12
Quercus phellos	Tubeling	Naturescapes Wetland Plants	Suffolk, VA	1.25		24	6	22	52
Salix nigra	Bare root	Warren County Nursery	McMinnville, TN	0.45		21	7	1	29
Salix nigra	Gallon	Naturescapes Wetland Plants	Suffolk, VA	5		5	3	3	11
Salix nigra	Tubeling	Pinelands Nursery	Columbus, NJ	1.1	1	16	3	3	22

Appendix 4. Percent change in height graphs




Saturated Cell
Percent Change in Height
600
500
400
300
200
100
0
-100
Bare root
Gallon
Tubeling
Tubeling NO SOIL
Betula nigra
Liquidambar styraciflua
Platanus occidentalis
Quercus bicolor
Quercus palustris
Quercus phellos
Salix nigra
2009 % Height
2010 % Height
2011 % Height
2012 % Height
2013 % Height


Flooded Cell
Percent Change in Height
150
130
110
90
70
50
30
10
-10
-30
-50
Bare root
Gallon
Tubeling
Bare root
Gallon
Tubeling
Bare root
Gallon
Tubeling NO SOIL
Bare root
Gallon
Tubeling
Bare root
Gallon
Tubeling
Bare root
Gallon
Tubeling NO SOIL
Bare root
Gallon
Tubeling NO SOIL
Betula nigra
Liquidambar styraciflua
Platanus occidentalis
Quercus bicolor
Quercus palustris
Quercus phellos
Salix nigra
2009 % Height
2010 % Height
2011 % Height
2012 % Height
2013 % Height


Field Study
Percent Change in Height
150
130
110
90
70
50
30
10
-10
-30
-50
Bare root
Gallon
Tubeling
Tubeling NO SOIL
Betula nigra
Liquidambar styraciflua
Platanus occidentalis
Quercus bicolor
Quercus palustris
Quercus phellos
Salix nigra
2009 % Height
2010 % Height
2011 % Height
2012 % Height
2013 % Height

Appendix 5. List of presentations, posters and student reports

VIMS Student and Faculty Presentations and Posters

Invited Presentations

Hudson III, H. W., S. P. Charles, and J. E. Perry. 2013. Development of wetland structure and ecological functions in created palustrine forested wetlands: A large scale field experiment in Virginia, USA. Invited presentation at Wetland Studies/Peterson Foundation Wetland Mitigation Research Symposium in Gainesville, VA.

Perry, J. E. 2010. Primary Ecological Succession in Tidal and Non-tidal Wetlands. Univ. Virginia Dept. Environmental Science Seminar Series. Charlottesville, Virginia, USA.

Abstract: With losses of wetlands in the United States continuing to be problematic, efforts to minimize the net loss of ecological and societal functions remain focused on the creation or restoration of similar habitats. In order to provide a manageable protocol for monitoring the success of created or restored wetlands, emphasis is now being directed towards establishing "reference" sites that are representative of regional and local conditions. Unfortunately, little effort has been made to better understand the role of primary- and secondary-succession in the time period over which created or restored wetlands would resemble natural, mature systems. This project, in part, examined the early primary-succession properties of a chronosequence of three tidal oligohaline salt marshes and primary- and secondary-succession of 17 forested wetlands. Vegetation in primary-succession tidal wetlands, as well as net carbon exchange, equaled natural systems within the first few years of establishment, while carbon sequestering may take longer than existing models indicate. In the secondary-succession forested wetlands, ordinations indicated three general types of communities in the mid-Atlantic states: one dominated by bald cypress (*Taxodium distichum*) and water tupelo (*Nyssa aquatica*), one dominated by black willow (*Salix nigra*), and one with a species composition similar to that of a mature stand of bottomland hardwoods. Data on primary succession in the forested wetland showed a large variation in vegetation community dynamics, but no similarity to secondary-succession or mature forested wetlands. The latter finding throws into question the wisdom of using existing mature non-tidal wetlands as reference sites.

Perry, J. E. 2010. Quantifying the replacement of lost wetland functions in Created and Restored Wetlands: the role of science in policy and regulatory decisions. Society of Ecological Restoration Mid-Atlantic Section Annual Meeting. Invited Keynote Speaker. College Park, Maryland, USA.

Abstract: Wetlands are known to serve numerous important ecological functions, including their ability to store carbon, provide habitat through species diversity, and provide nutrient cycling. Wetland protection, which started with the Clean Water Act of 1972 (through both regulatory and court interpretation), now requires that the destruction of wetlands for the purpose of profit must be avoided or the functions that the wetlands served the ecosystem must be replaced by mitigation; that is the lost ecological functions must be replaced by creating a new wetland or restoring a non-functional wetland that would then be expected to provide the lost functions. Therefore, since the late 1980's "No net loss" has become the mantra of federal and state wetland regulators. Currently, regulatory emphasis has been placed on replacing wetlands (mitigation) instead of avoiding them. This has lead to the construction (and to a minor degree, restoration) of many acres of tidal and non-tidal wetlands throughout the US over the past several decades. Unfortunately, it is only within the last decade that we have been able to take a close look at whether these created and restored wetlands actually do replace lost ecological functions. Initial data indicates that some simple functions, such as species richness and vegetation biomass, may be obtainable. However, data on more complex functions, such as nutrient processes and vegetation composition, are less promising. As scientists, we need to start providing more quantitative data to determine which ecological functions are being successfully replaced by creation and/or restoration and to identify those that are not. We also need to find a way to better present the results of our work to the policy makers and regulators who are tasked to write and enforce our wetland protection/mitigation laws in an understandable format. Without doing so, we may find that we are leveraging the long term ecological services of our wetlands for short term economic gain.

Conference and Meeting Presentations

Hudson III, H. W. and J. E. Perry. 2013. Restoration of Forested Wetland Structure and Function Through Tree Planting: A Large Scale Field Experiment in Virginia. Society of Wetland Scientists Annual Meeting. Duluth, MN.

Abstract: Wetland structure and ecological functions may not develop in restored forested wetlands as a result of inadequate tree establishment and reduced growth. Planted tree survival and growth is influenced by species/stocktype selection and environmental conditions. To determine the effect of these factors on restoring ecosystem structure and functions in forested headwater wetlands a large scale hydrologically manipulated field experiment was planted with 2,772 seedlings of *Betula nigra*, *Liquidambar styraciflua*, *Platanus occidentalis*, *Quercus bicolor*, *Quercus palustris*, *Quercus phellos* and *Salix nigra*, using three stocktypes (bareroot, tubeling, and 1 gallon containers). Survival and morphology was monitored over four growing seasons and 351 trees were destructively sampled to measure woody biomass. There was a significant positive relationship between basal diameter (at ground line) and woody biomass ($p<0.001$, $r^2=0.7446$) that was used to determine primary productivity of surviving trees. Restoration of structural components (canopy diameter, height and ground line diameter) and primary productivity differed among species and stocktypes. Initial differences among the stocktypes diminished through time. Gallon containers were typically larger and had greater survival than the bareroot or tubeling stocktypes. These results suggest that species and stocktype selection will influence the restoration of ecosystem structure and functions but the importance of stocktype selection diminishes through time.

H. W. Hudson, III and J. E. Perry. 2012. Two Year Survival and Growth of Seven Wetland Tree Species in Three Hydrologically Distinct Habitats. Society for Wetland Scientists. Annual Meeting. Orlando Florida. June 3-8.

Abstract: Success criteria for forested wetland compensation for Virginia, USA, mitigation banks requires 1) a tree density of >495 stems/ha and 2) a minimum increase in height of 10% per year. The purpose of this study, in part, was to investigate the survival and growth of different woody species and planting types. A long term large-scale mesocosm study consisting of three hydrologically distinct Cells (Ideal, Saturated, and Flooded) was established in New Kent, Co., Virginia, USA. Plantings consisted of seven woody species (Betula nigra, Liquidambar styraciflua, Platanus occidentalis, Quercus bicolor, Q. palustris, Q. phellos, and Salix nigra) and three planting types (bare root, tubeling and 1 gallon). A total of 2772 saplings (44 trees of each species planting type combination for a total of 924 saplings per Cell) were planted in the Spring of 2009. Survival and growth (height, canopy diameter, and basal diameter) of all trees were measured three times per year. There was significant three-way interaction among Cell, species and planting type when analyzing both probabilities of survival ($p<0.0001$) and relative growth rates (RGR) at 18 months ($p<0.0001$). Therefore, additional comparisons were performed within each Cell resulting in significant two-way interaction among species and planting type, suggesting that survival and growth was not uniform across species and planting types. Gallon planting type had greater survival probability and relative growth rates while the bare root and tubeling had decreased survival and growth. Betula nigra exhibited increased growth in the Ideal and Saturated Cells, while S. nigra exhibited increased survival and growth in the Flooded Cell. The percentage of all trees that satisfied the minimum 10% increase in height per year in the Ideal, Saturated and Flooded Cells was 58.9%, 50.0% and 26.9%, respectively. These results suggest that depending on the particular requirements (survival or growth) of forested wetland compensation sites, the most appropriate woody planting stock depends on site hydrology, species and planting type in combination and that the minimum woody growth rate in Virginia may be difficult to obtain in very wet sites.

S. P. Charles, J. E. Perry. 2012. Soil Characteristics and Tree Growth in a Created Wetland. Society for Wetland Scientists. Annual Meeting. Orlando Florida. June 3-8.

Abstract: Forested wetland sites created for mitigation exhibit varying degrees of success. Unsuccessful attempts at mitigation often fail due to a combination of poor tree selection as well as environmental site conditions. This project aims to identify factors affecting mitigation success through a long-term mesocosm study at the New Kent Forestry Center in New Kent, Virginia. One key factor is how primary and secondary successional species (in this case Betula nigra and Quercus palustris) respond to being transplanted into different environmental conditions. 44 trees of each species were transplanted into three sites bearing distinct hydrologic and soil characteristics (ideal, saturated, and flooded conditions). After 2 years soil was tested for N, P, C, C:N ratio and bulk density. The Cells showed significant differences ($p<.0001$) in all soil criteria except for P, in which the saturated and ideal Cells were similar. Soil carbon and C:N ratios increased from the flooded Cell to the saturated Cell and are highest in the ideal Cell. Nitrogen content and bulk density showed the opposite trend. Carbon content and C:N ratio showed significant positive correlation with tree height growth, while bulk density showed the expected negative correlation. Interestingly, nitrogen content showed negative correlation with tree growth. Negative nitrogen to growth trends may be explained by an imbalance in the soil. These findings have important implications for site selection and preparation in created wetland sites.

Hudson III, H. W., S. P. Charles, J. E. Perry and R. B. Atkinson. 2011. Modeling growth rates of woody wetland plants common to the Piedmont region of the Mid-Atlantic States. Society of Ecological Restoration Mid-Atlantic 6th Annual Conference. College Park, Maryland.

Abstract: Success criteria in Virginia for forested wetland compensation requires a tree density of >495 stems/ha. The purpose of this study was to investigate which woody species and planting types survive and grow best in compensatory wetlands. A long-term large-scale mesocosm study consisting of three hydrologically controlled Cells (Ideal (IC), Saturated (SC), and Flooded (FC)) was established in New Kent County, Virginia and three compensatory wetland (CW) sites in Loudoun County, Virginia were selected for comparison against mesocosm. All were planted in Spring of 2009 with seven wetland tree species (*Betula nigra, Liquidambar styraciflua, Platanus occidentalis, Quercus bicolor, Q. palustris, Q. phellos,* and *Salix nigra*) of three planting types (bare-root, tubeling, 1-gallon) totaling 2,772 trees in the mesocosm and 1,596 in the CW. After two growing seasons, survival and growth rates in the mesocosm were generally greater than those in the CW. *Salix nigra* had greatest survival in FC (83.5%) and *Q. bicolor* greatest in IC (70.5%), SC (85.9%) and CW (78.9%). In the mesocosm, survival of the 1-gallon planting type (92.2%) was greater than that of tubeling (59.4%) and bare-root planting type (65.4%). Similarly, survival of the 1-gallon (76.9%) was greater than tubeling (51.5%) and bare-root planting type (48.7%) in the CW. *Betula nigra* (1-gallon) had the greatest increase in height (7.7 cm/month), basal diameter (0.28 cm/month) and canopy diameter (6.0 cm/month) in the mesocosm, while in the CW, *S. nigra* (bare-root) had the greatest increase in height (1.6 cm/month), *S. nigra* (1-gallon) the greatest increase in basal diameter (0.06 cm/month) and *B. nigra* (tubeling) the greatest increase in canopy diameter (1.0 cm/month). The lower survival and growth rates in the CW may have resulted from factors associated with site hydrology, soil properties and herbaceous competition, which are under investigation. These results suggest that several species and planting types may be appropriate for forested compensatory wetlands in Virginia.

Hudson III, H. W. and J. E. Perry. 2011. Growth and survival of seven wetland tree species in three hydrologically distinct habitats. South Atlantic and Mid Atlantic Chapters Society of Wetland Scientists Regional Meeting. Reston, Virginia.

Abstract: Success criteria in Virginia for forested wetland compensation requires a tree density of >495 stems/ha. In order to investigate which species and planting types survive and grow successfully in three controlled hydrologic conditions (Ideal, Saturated, and Flooded), a long term large scale mesocosm study consisting of three Cells were planted in the Spring of 2009. A total of 924 trees were planted in each Cell and consisted of 44 plantings of each species (*Betula nigra, Liquidambar styraciflua, Platanus occidentalis, Quercus bicolor, Q. palustris, Q. phellos,* and *Salix nigra*) and three different planting types (bare root, tubeling, 1 gallon, 308 of each species per Cell) for a total of 2772 planted trees. The overall percent survival of all planted trees after two growing seasons was 72.3 %. Within each of the Cells the gallon planting type had greater survival than bare root and tubeling planting types. *Salix nigra* had greatest percent survival in the Flooded Cell and *Q. bicolor* had greatest percent survival in the Ideal and Saturated Cells. Basal diameter, height and canopy diameter growth rates increased during the second growing season. *Salix nigra* had the highest growth rate in the Flooded Cell and *B. nigra* the highest in the Ideal and Saturated Cell. After two growing seasons *S. nigra* and the gallon planting type of all species exhibited greater percent survival and growth rates suggesting that they may be appropriate planting stock for forested compensatory wetland sites in Virginia.

Wurst, S.J., J.D. Roquemore, H.W. Hudson, III, J.M. Campo and R.B. Atkinson. 2011. Tree survival and growth in created wetland mitigation sites in Virginia: a field validation study. South Atlantic and Mid Atlantic Chapters Society of Wetland Scientists Regional Meeting. Reston, Virginia.

Abstract: Poor survival and slow growth rates of planted woody vegetation in forested wetlands have been a major limitation of created forested wetland performance. Few studies have addressed how planting material (species and planting type) affects the survival and growth of woody species. Species including *Betula nigra, Liquidambar styraciflua, Platanus occidentalis, Quercus bicolor, Q. palustris, Q. phellos,* and *Salix nigra* were planted as bare root, potted (3.8-L pots), tubeling with soil around the roots, and tubeling without soil around the roots. Three wetland mitigation sites were selected for planting in the northern Piedmont physiographic province of Virginia. Planting occurred on March 9-10, 2009 and survivorship and growth (canopy width, stem width at base, and height) of individual trees was monitored immediately after planting and also in Aug 2009 and 2010. There were 1594 trees planted and 942 survived both growing seasons (59% survival). Two-way analysis of variance found *Q. phellos* tubelings had the lowest overall survival (17.1%) while *Q. bicolor* potted had the highest survival (96.1%). Bare roots had the lowest survival (48.7%) while the potted planting type had the highest survival (76.9%). *P. occidentalis* potted showed the worst overall change in height (-3.9 cm/month) while *S. nigra* bare root had the highest height change (1.6 cm/month). Knowledge of the woody plants and initial planting types that result in optimum density will help improve future forested wetland compensation projects. Further analysis of field conditions at these sites is planned in order to improve selection of planting materials.

Conference and Meeting Posters

Hudson, H. W. III, and J. E. Perry. 2012. Two year survival and growth of seven wetland tree species in three hydrologically distinct habitats. 9th Annual INTECOL/SWS International Wetlands Conference. Orlando, FL.

Hudson, H. W. III, and J. E. Perry. 2011. Growth and Survival of Woody Wetland Vascular Plants: A Large Scale Mesocosm Study. Virginia Association of Wetland Professionals Annual Meeting. Richmond, VA.

Charles, S. P. and J. E. Perry 2011. Quantifying Growth and Survival of Wetland Tree Species Grown Under Separate Hydrological Regimes. Society of Wetland Scientists South Atlantic Chapter Annual Meeting. Reston, VA. USA.

Abstract: When creating or restoring forested wetlands in the Mid-Atlantic region of the US, a wide variety of tree species and planting types are used. To help identify the most appropriate trees to use we have established a long term mesocosm study in New Kent, Virginia. Constructed in 2009, the study includes 2772 saplings of seven tree species (*Betula nigra, Liquidambar styraciflua, Platanus occidentalis, Quercus bicolor, Q. palustris, Q. phellos,* and *Salix nigra*) common to the Piedmond Provence of Virginia. 924 saplings of each species were planted in three hydological regimes (Ideal, Saturated in root zone, and Flooded). These included 308 saplings of three planting type (bare root, tubeling, and gallon). Canopy cover, basal diameter, height, and above and below ground biomass were collected as growth measurements.

After two years of data we found that, as expected, wetter hydrology led to decreased survival and growth rates. Ideal Cell showed highest growth followed by the Saturated and Flooded Cell. Similarly, the Flooded Cell exhibits the lowest survival rate (65.4% survival over two growing seasons), while the Saturated Cell showed highest survival (80.2%) and the Ideal Cell fell between the two (71.2%). Gallons had the highest survival (92.2%) followed by bare roots (65.4%) and then tubelings (59.4%). *Salix nigra* had the highest survival rate in the Flooded Cell, while *P. occidentalis* had the lowest. The results of this data help to quantitatively determine which woody species, and planting type, would prove the most useful in forested wetland compensation in the Mid-Atlantic US.

College Class Presentations and Posters

Moses, M. Bromberg-Martin, B. Frye, K. 2010. Growth Rate Comparison of *Salix nigra* and *Quercus palustris* in Three Hydrologic Conditions of Created Wetlands. Christopher Newport University BIO 306 Class Poster and Project.

Ernst, C.B. Wildasin, A. Gray, J. Danielson, A. Ledin, and D. Bernhalter. 2011. Preliminary Results: Evaluating the Productivity of Seven Wetland Tree Species in a Created Wetland Site Through an Analysis of Above and Below Ground Biomass. Christopher Newport University BIO 306 Class Poster and Project.

Swinford, J., Gotschalk, E., Tomlinson, C., Janney, H. and Ekholm, K. 2012. Preliminary Data: Preferential Bark Peeling Behaviors of the European Hornet (*Vespa crabro*) and Their Effect on Health of River Birch. Christopher Newport University BIO 306 Class Poster and Project.

Wilson, J., Stephens, L., Garrison, C., Dwight, D., Seward, M. and Muench, R. 2013. The Effect of Water Stressors on Pathogen Susceptibility. Christopher Newport University BIO 306 Class Poster and Project.

High School Projects

Theuerkauf, E. J. 2012. The effects of distance to the adjacent forest on the height and growth rate of planted trees. Gloucester High School. Governor School Program.

Grzegorczyk, Shane. 2011. Effects of Initial Tree Size on Survival of Seven Wetland Tree Species. Charlottesville High School. Governor School Program

Clayborne, Chris. 2011. The Effect of Water Stress on Tree Root Growth. Gloucester High School Senior Board Project.

CNU Student and Faculty Presentations and Posters

Wurst, S., J. D. Roquemore, G. Noe, and R. B. Atkinson. 2013. Analyzing soil parameters to enhance tree growth and design plans for created wetlands in the Piedmont Province. Invited presentation at Wetland Studies/Peterson Foundation Wetland Mitigation Research Symposium in Gainesville, VA.*

*Partly supported by separate Peterson Foundation Contract

Bowen, B., J. Roquemore, and R. B. Atkinson. 2012. Floristic composition of a created wetland in Loudoun County, Virginia. 14th Annual Mid-Atlantic Regional Conference of Undergraduate Scholarship, Sweet Briar College, Virginia.

Priebe, J., S. Wurst, and R.B. Atkinson. 2012. Using ‘rusty rods’ as a measure of hydrology in a created wetland in Loudoun County, VA. 14th Annual Mid-Atlantic Regional Conference of Undergraduate Scholarship, Sweet Briar College, Virginia.

Seidel, M., J. Roquemore, and R. B. Atkinson. 2012. Survival and growth of seven tree species from three stocktypes planted in created wetlands in Loudoun County, Virginia 14th Annual Tidewater Student Research Poster Session, Christopher Newport University, Virginia.

*Wurst, S., J. Roquemore, and R.B. Atkinson. 2011. A characterization of soils in created wetlands in Loudoun County, Virginia. MARCUS, Sweet Briar College, Sweet Briar, Virginia.

Abstract: Soil compaction and low nutrient availability have hindered efforts to create functioning wetlands. The purpose of this study is to characterize soils at three created wetlands to determine the effect of soil variables on growth. Seven species of trees were planted as bare roots, potted (3.8-L) pots, or tubelings at sites in Northern Virginia. Planting occurred on March 9-10, 2009 and growth of individual trees was monitored immediately after planting and each subsequent August. Soil samples were gathered at the sites this May. The samples went through a KCl extraction to measure Nitrogen levels as well as a Mehlich 3 extraction to measure Phosphorus. Samples were also run through a LISST to quantify the particle sizes in the soil. Averages for bulk density (1.04±0.14), Nitrate/Nitrite (3.6±3.7) and Potassium (66.1±64.3) suggest that each may influence observed growth trends among tree species.

Atkinson, R.B., H.W. Hudson, III and J.E. Perry. 2010. Tree survival and growth in created wetland mitigation sites in Virginia. Presented at Association of Southeastern Biologists Annual Meeting, Asheville, NC.

Hudson III, Herman W. and R.B. Atkinson. 2010. The effect of adjacent forests on colonizing tree density in restored wetland compensation sites in Virginia. Presented at Association of Southeastern Biologists Annual Meeting, Asheville, NC.

Hudson, H.W., III and R.B. Atkinson. 2010. The effect of adjacent forests on colonizing tree density in restored wetland mitigation sites in Virginia. SigmaXi, Newport News, VA.

Perry, J.E., R.B. Atkinson, L. Sutter, H.W. Hudson, and S. Charles. 2010. Assessment of woody vegetation for replacement of ecological functions in created forested wetlands of the Piedmont Province of Virginia. Annual Meeting of the Virginia Association of Wetland Professionals, Williamsburg, VA.

Wurst, S., and R.B. Atkinson. 2010. Survivorship of seven tree species in three planting types planted in Northern Virginia. MARCUS, Sweet Briar College, Sweet Briar, Virginia.

Wurst, S., H.W. Hudson, J. Roquemore, and R.B. Atkinson. 2010. Tree survival and growth in created wetland mitigation sites in Virginia: A field validation study. South Atlantic/Mid-Atlantic Society of Wetland Scientists Joint Chapter Meeting, Reston, VA.

Heeter, F., T. Brubach, J. Coley, H. Hudson III, I. Knight, D. Riedl, J.D. Roquemore, K. Sweet, S. Wurst and R.B. Atkinson. 2009. Evaluation of planted tree morphometry within three wetland compensation sites in the Piedmont Region of Virginia. Paideia, Newport News, VA.

Hudson, H.W., III and R.B. Atkinson. 2009. The effect of adjacent forests on colonizing tree density in restored wetland mitigation sites in Virginia. International Meeting of the Society of Wetland Scientists in Madison, Wisconsin.

Knight, I., and R.B. Atkinson. 2009. Growth of seven wetland tree species in three compensatory wetlands in Northern Virginia. MARCUS, Sweet Briar College, Sweet Briar, Virginia.

Hudson, H.W., III and R.B. Atkinson. 2009. The effect of surrounding forests on colonizing tree density in restored wetland mitigation sites in southeastern Virginia. Virginia Council of Graduate Schools, Graduate Student Forum in Richmond.

Merz, N. Hudson, H.W., III and R.B. Atkinson. 2009. First-year survivorship of seven wetland tree species in three non-tidal freshwater wetland compensation sites in Loudoun County, Virginia. MARCUS, Sweet Briar College, Sweet Briar, Virginia.

*(NOTE: The Wurst et al. (2011) and Wurst et al. (2013) papers addressed both the recently-funded-by-Peterson-Foundation research on explanatory variables that is not part of the contract we are reporting on; however, some of the tree survival and growth findings were discussed in that presentation.)