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

2014 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. to determine the appropriate vegetative measures that will identify whether the important wetland functions are being replaced.
3. to 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 six growing seasons, and survival and morphological results from the Mesocosm and Field site suggest the primary successional species (excluding *P. occidentalis*) grown in gallon containers are the best choice for establishing productive trees in created forested wetlands. 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. Additional analysis found that average basal diameter is a good predictor of total tree biomass of seedlings and that beavers can increase mortality of larger basal diameter planted trees.

In 2014, one oral presentation and one poster presentation were delivered at local and regional conferences by a graduate student from VIMS (Appendix 4). Over six years ~200 students, Master Naturalists, Master Gardeners, Boy Scouts and Girl Scouts have visited and helped collect data at the Mesocosm. Currently one CNU graduate students is designing his thesis at the Field site and one Ph.D. student is currently completing his dissertation research at the Mesocosm. Two Masters students from CNU successfully defended their thesis focusing on the Field site and graduated in May. Finally, one publication was accepted and published in Ecological Engineering and a second is being prepared for submission to Restoration Ecology (Appendix 5).

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 gallons 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

The most common woody planting stock (stocktype) used in restored forested wetlands, bare-root seedlings, 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.

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 (Ambient 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 Ambient and Flooded cell conditions are meant to provide data that will allow us to determine optimal, least hydrological stressed (Ambient 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 (Ambient) and lower (Flooded) limits of survival and growth that would be expected in the Saturated cell and the Field study. 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).

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 is to relate woody growth (via morphometric analysis) as a dependent variable to two independent ecological variables (biomass, both above and belowground; and, 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, direct measurements of each of these functions in the field is time consuming and destructive (i.e. requires cutting and removing of vegetation). Therefore, many authors and regulatory agencies 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 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) to determine the role volunteer woody plants in created forested wetlands by using a chronosequence of sites in the Piedmont and 2) to determine 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.).

<u>Preliminary Studies</u>

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 when compared to those at soil level or in 15-cm ditches. Bailey et al. (2007) came to similar conclusions in a created hardwood swamp: microtopography 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-dominated 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 few methods exist which allow tracking of individual trees across years (Peet et al. 1998, Bailey et al. 2007). In this study we are applying their techniques to help refine our understanding of the response of various species and planting materials to experimental conditions (Mesocosm) and conditions found in recently restored/created wetlands (Field 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.

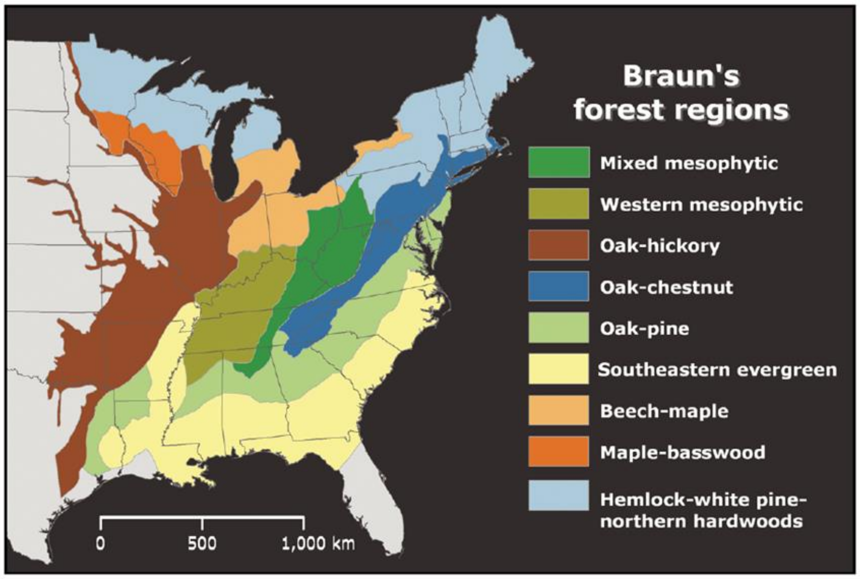

Figure 1. Nine regions described by Braun (1950), representing original forests of eastern North America.

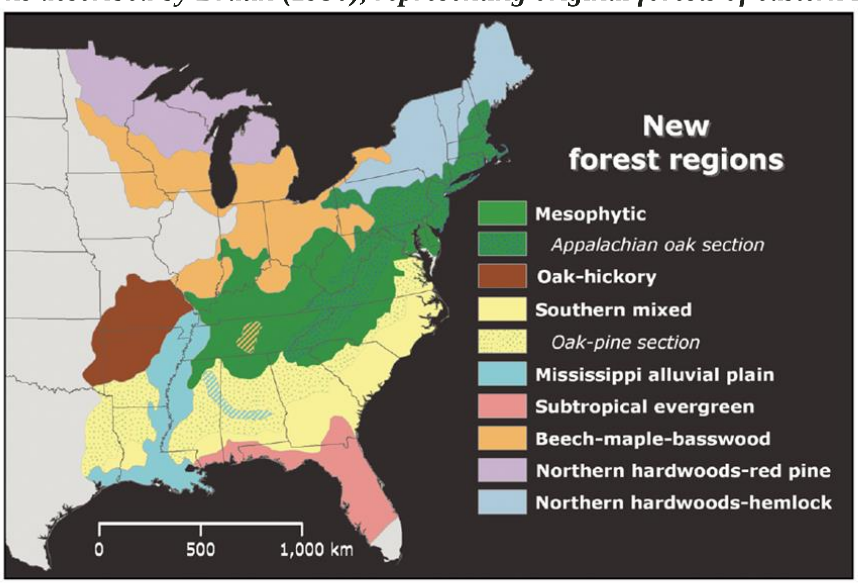

Figure 2. Regions derived from contemporary forest data. The cross-hatching in the Nashville Basin and the black belt region indicates inclusions in the larger forest regions—areas with affinities to the noncontiguous region with the same color as the cross-hatching (from Dyer 2006).

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 is being updated yearly throughout the life of the study and is conducted primarily by Herman Hudson, the VIMS doctoral student, and overseen by the PIs.

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 Mr. 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, 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 472ft). Soil of the Ambient 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 Ambient 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 Ambient and Saturated cells are mowed approximately every ten days and herbicide (Roundup®) was applied at the rate specified on the package label near 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 called for 3 study sites with 525 trees planted at each site for a total of 1575 individuals. High priority was given to consistency in terms of 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 and extra plots were added at Phase III.

Mortality and morphometric data were collected using methods modified from Bailey et al. (2007). Each tree was mapped using an x- and y- coordinate grid system to aid with location throughout the study. 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 March of 2009 and again in August of each subsequent year. Analysis of the data collected from the Field study was conducted independently to identify which species and planting type performed best in these field conditions.

<u>Planting Material</u>

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.

Mesocosm

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).

Field

The trees planted in the Field study were from the same sources as the trees planted in the Mesocosm study, consisting of the same seven species and stocktypes, which totals 21 (7 x 3) experimental units. Each site is completely replicated and randomized in each plot. Planting was completed in early March 2009 in conjunction with the Mesocosm study. No harvesting or replanting has occurred in the Field study.

At Phase I, 4 plots each containing 3 subplots with 21 trees (a complete subsample) in each subplot (252 trees) were installed in March 2009. Another study was being conducted in the two northern sections of the phase eliminating them as a possibility for this study. The size of the remaining area was not adequate to fit 525 trees with the 8-ft spacing requirement. The first post-construction growing season at Phase I was 2007 and the study trees were planted before the beginning of the third growing season (2009).

At Phase II, 4 plots each containing 3 subplots with 21 trees (252 trees) were installed in March 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 trees with the 8-ft spacing requirement. The first growing season at Phase II was 2008 and study trees were planted before the beginning of the second growing season (2009).

At Phase III, fairly uniform hydrology and vegetation provided enough space to fit the remainder of the trees and maintain the required 8-ft spacing. Therefore, 17 plots were established, each containing 3 or 4 subplots with 21 trees per subplot (1092 trees in this Phase) were installed in late winter 2009. The first growing season at Phase III was 2008 and the study trees were planted in 2009, before the beginning of the second growing season.

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 above and belowground biomass were measured. At the Field study sites, the herbaceous vegetation was analyzed during the August sampling period from 2012 through 2014.

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 (height of highest stem, canopy diameter andbasal stem diameter at soil level) 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 and Field plantings (often leading to negative growth rates) and were noted during sampling.

Percent change in height per year was calculated to eliminate any size related growth differences when comparing species and stocktypes (Hunt 1990). Percent change in height was calculated for each year using the following equation: $((H_{final}-H_{initial})/H_{initial})*100$, where $H_{initial}$ is the preceding August height measurement and H_{finial} is the August height measurement for the year being calculated. However, for 2009 $H_{initial}$ refers to the April measurement following planting and the rate was calculated per day and then extrapolated to an entire year. 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, percent phosphorus, percent sand, percent, silt, and percent clay.

Results

<u>Environmental Conditions</u>

Several physical and chemical characteristics of the environment were measured at the Mesocosm cells and Field sites.

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, therefore accurate data collection did not start until October 2013. 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. A single probe failed after March 2014 (Saturated B probe).

The data suggest that the percent volumetric water content can increase rapidly after rainfall or irrigation and then decrease quickly within the Saturated cell (Figure 3, Figure 4, Figure 5). The probe in the Flooded cell did not fluctuate as dramatically, possibly as a result of the perched water table and higher clay content. These results suggest that there are differences in the hydrologic treatments among the cells and that the hydrology is not uniform within the Saturated cell.

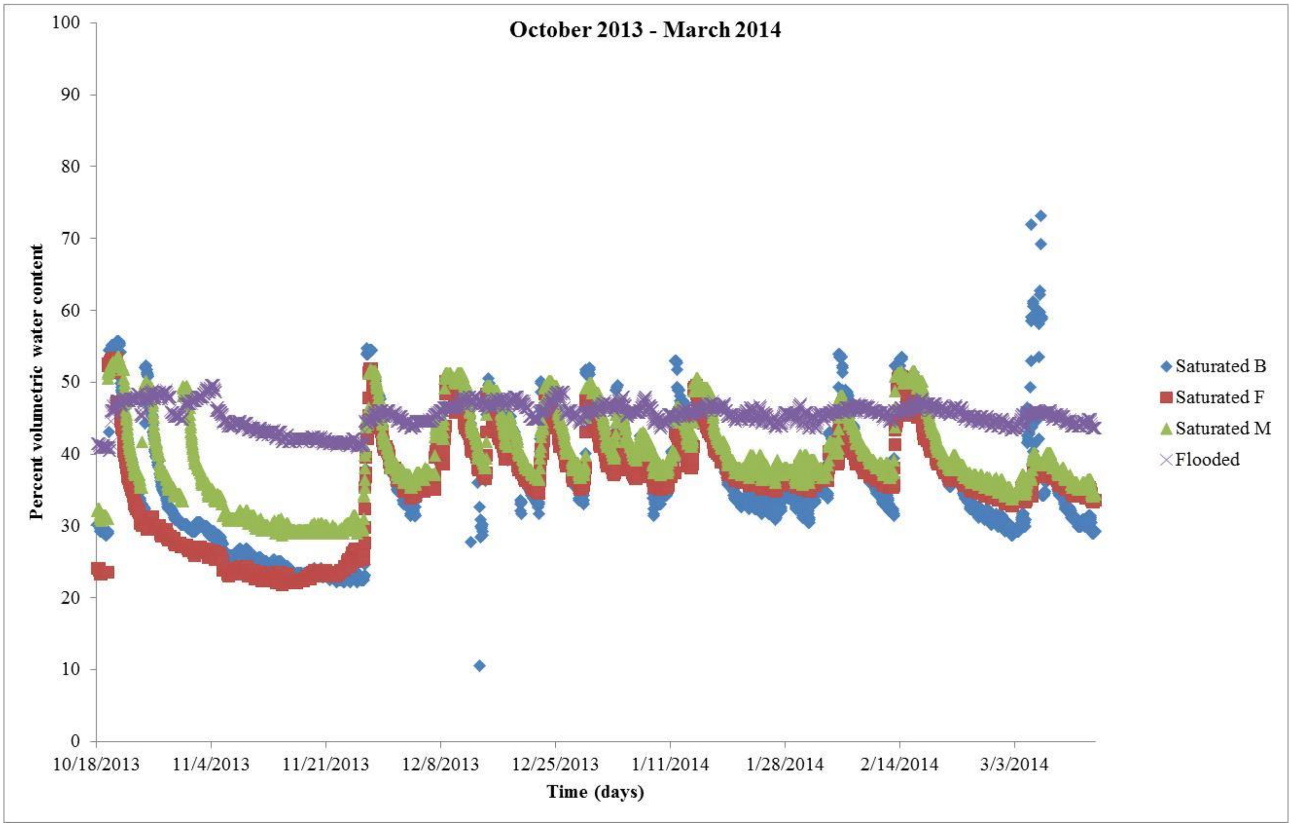

Figure 3. Percent volumetric water content from soil moisture test probes for October 2013 through March 2014.

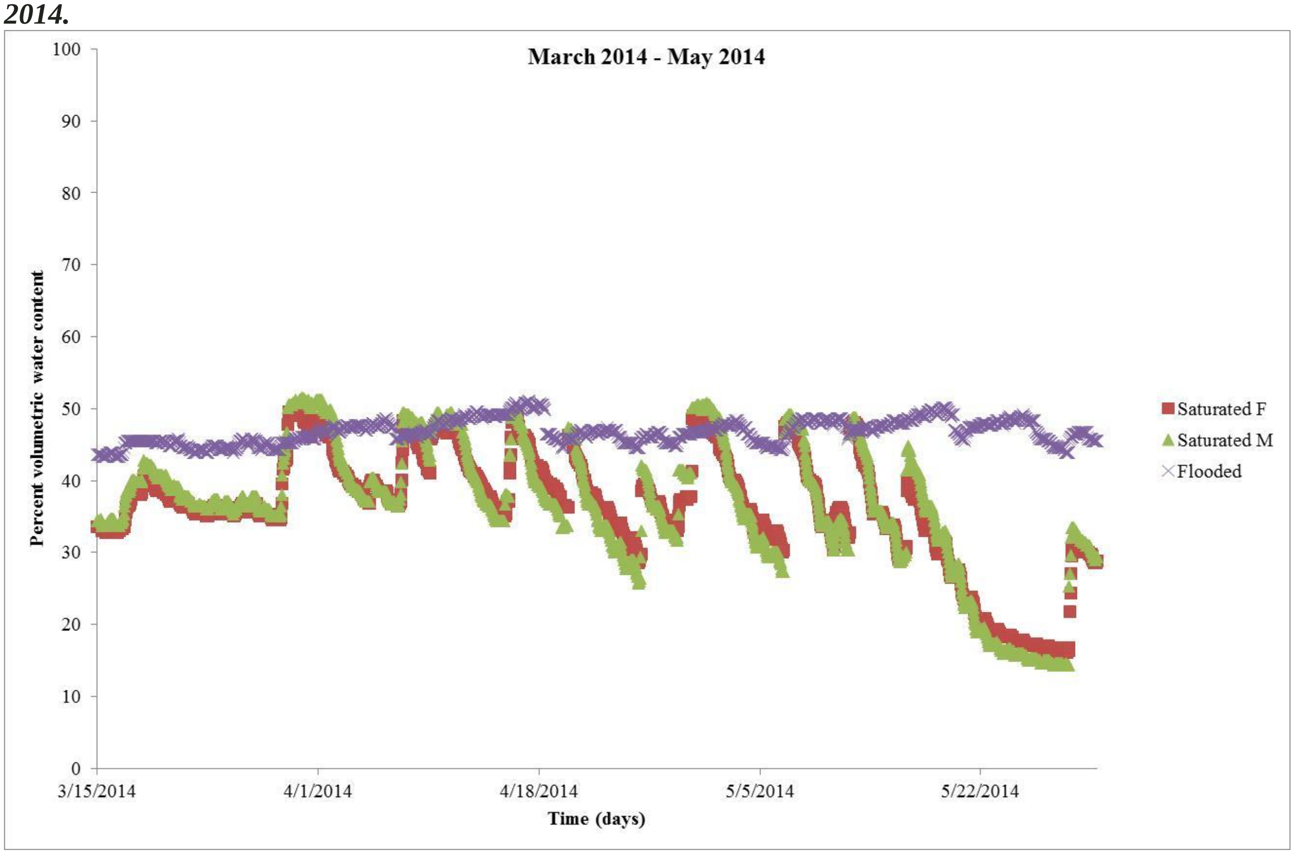

Figure 4. Percent volumetric water content from soil moisture test probes for March 2014 through May 2014.

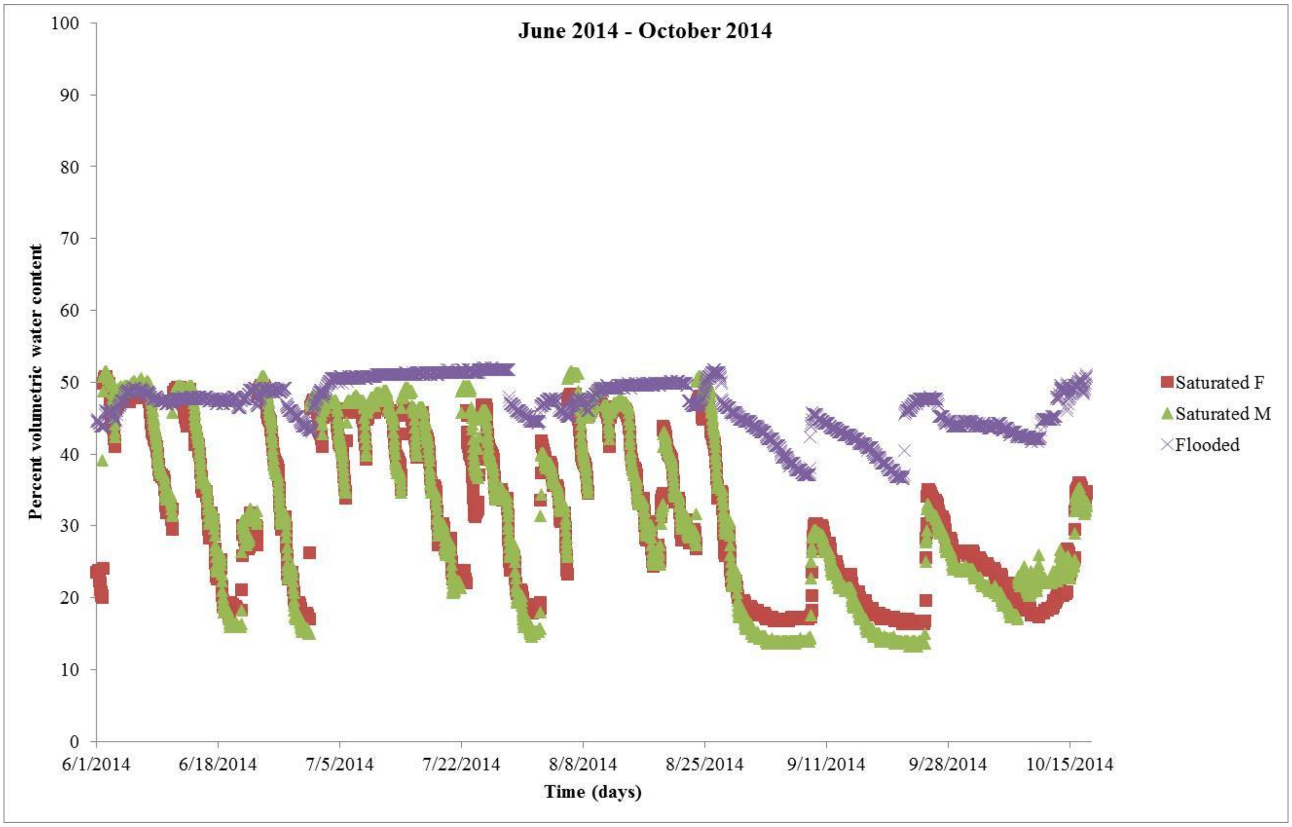

Figure 5. Percent volumetric water content from soil moisture test probes for June 2014 through October 2014.

Soil

Soil analysis of the Mesocosm suggests that there are differences in the soil physical and chemical properties among the cells (Table 1). The bulk density and clay content is slightly higher in the Flooded cell than the Saturated and Ambient cells. The percent phosphorus, carbon, and nitrogen are lower in the Flooded cell compared to the Saturated and Ambient cells.

The lower nutrient concentrations and high bulk density in the Flooded cell are most likely the result of topsoil removal during construction which was accomplished using heavy machinery.

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

The differences in soil characteristics within and among cells may influence tree survival and growth and future analysis of survival and growth will seek to model the effect of both variables simultaneously.

Table 1. Soil characteristics of the cells in the Mesocosm

	Ambient Cell	Saturated Cell	Flooded Cell
Hydrology	Recevied only precipitation	Kept saturated for a minimum of 90% of the growing season within the root-zone (10cm) of the plantings and irrigated as needed	Inundated above the root crown for a minimum of 90% of each year
Soil Preparation	Disked and Tilled	Disked and Tilled	Excavated to a depth of 1m (3.1ft.) to an existing clay layer
Herbaceous Vegetation Control	Riding Lawnmower, Push mower, weedwacker, Glyphosate application	Riding Lawnmower, Push mower, weedwacker, Glyphosate application	None
Bulk Density (g/cm^3) Range	0.82 -- 1.3	0.84 -- 1.5	1.1 -- 1.8
Percent Sand Range	54.6 -- 91.5	75.9 -- 94.0	42.0 -- 87.7
Percent Silt Range	2.8 -- 38.3	3.3 -- 16.2	1.2 -- 27.8
Percent Clay Range	2.7 -- 8.2	2.3 -- 8.9	5.5 -- 32.6
Percent Carbon Range	0.74 -- 2.16	0.29 -- 2.39	0.13 -- 0.69
Percent Nitrogen Range	0.09 -- 0.25	0.07 -- 0.23	0.03 -- 0.13
Percent Phosphorus Range	0.17 -- 0.52	0.10 -- 0.52	0.10 -- 0.25

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

Based on the initial planting density in this study (692 stems/acre in the Mesocosm, 681 stems/acre in the field study), survival would need to exceed 58.8% in order to satisfy the required >400 stems/acre. For this analysis only those species/stocktype combinations exhibiting greater than 58.8% survival qualify as appropriate selections for planting. However, initial density could be increased to overcome poor survival.

Mesocosm

After six years all species grown in the gallon containers had >58.8% survival in the Ambient cell and Saturated cell (Table 2). In the Flooded cell only six species/stocktype combinations had >58.8% survival; the *B. nigra* gallon and tubeling, the *L. styraciflua* gallon, and all three stocktypes of *S. nigra.* After six years the highest survival rate was the gallon *B. nigra* and *Q. bicolor* in the Ambient cell (100% survival), *L. styraciflua* and *Q. bicolor* gallon in the Saturated cell (100%), and *S. nigra* gallon in the Flooded cell (94.7.1%). In year six there was very little decrease in percent survival, suggesting that the planted trees have become well established and adapted to the environmental conditions.

Field

In the Field study *Q. palustris* gallon had the greatest percent survival (76.3%) of any species/stocktype combination. The gallon stocktype of all species except *L. styraciflua* and *P. occidentalis,* had survival rates above the 58.8% threshold. All other stocktypes fell below 58.8% survival by 2014 with *Q. bicolor* tubeling falling below 58.8% survival for the first time in that year (Table 2).

Table 2. Percent survival for 2009 through 2014. Red represents <58.8% survival. Trees removed for biomass sampling in the Mesocosm were not included in the survival calculation.

		Ambient						Saturated						Flooded						Field					
Species	Stocktype	2009 % Survival	2010 % Survival	2011 % Survival	2012 % Survival	2013 % Survival	2014% Survival	2009 % Survival	2010 % Survival	2011 % Survival	2012 % Survival	2013 % Survival	2014 % Survival	2009 % Survival	2010 % Survival	2011 % Survival	2012 % Survival	2013 % Survival	2014 % Survival	2009 % Survival	2010 % Survival	2011 % Survival	2012 % Survival	2013 % Survival	2014% Survival
Betula nigra	Bare root	45.2	38.1	38.1	38.1	38.1	33.3	69.8	58.1	58.1	58.1	55.8	55.8	64.2	47.2	26.4	15.1	15.1	9.4	89.5	48.7	46.1	44.7	40.8	40.8
Betula nigra	Gallon	100.0	100.0	100.0	100.0	100.0	100.0	97.2	97.2	97.2	97.2	97.2	97.2	100.0	100.0	89.2	86.5	78.4	78.4	97.3	74.7	69.3	62.7	64.0	65.3
Betula nigra	Tubeling	29.0	25.8	25.8	25.8	25.8	25.8	81.3	75.0	75.0	71.9	68.8	68.8	93.9	90.9	72.7	72.7	69.7	66.7	89.5	50.0	48.7	47.4	47.4	43.4
Liquidambar styraciflua	Bare root	73.2	70.7	70.7	68.3	68.3	68.3	86.1	77.8	72.2	69.4	69.4	69.4	88.6	74.3	34.3	28.6	28.6	28.6	85.5	59.2	47.4	43.4	32.9	27.6
Liquidambar styraciflua	Gallon	100.0	94.9	94.9	94.9	94.9	92.3	100.0	100.0	100.0	100.0	100.0	100.0	100.0	94.6	81.1	73.0	75.7	70.3	94.8	77.9	67.5	66.2	45.5	42.9
Liquidambar styraciflua	Tubeling	19.4	13.9	13.9	13.9	13.9	13.9	60.0	45.0	37.5	35.0	35.0	35.0	91.2	79.4	44.1	41.2	41.2	47.1	57.9	21.1	21.1	19.7	13.2	13.2
Platanus occidentalis	Bare root	60.5	58.1	58.1	55.8	55.8	55.8	0.0	0.0	0.0	0.0	0.0	0.0	40.0	28.6	0.0	0.0	0.0	0.0	68.4	35.5	30.3	30.3	22.4	19.7
Platanus occidentalis	Gallon	92.3	84.6	84.6	82.1	82.1	82.1	97.4	97.4	97.4	97.4	94.7	92.1	81.1	43.2	21.6	10.8	13.5	10.8	68.0	45.3	37.3	34.7	32.0	33.3
Platanus occidentalis	Tubeling NO SOIL	96.7	96.7	96.7	96.7	96.7	96.7	74.2	74.2	67.7	64.5	64.5	64.5	41.2	17.6	0.0	0.0	0.0	0.0	90.8	59.2	50.0	48.7	42.1	40.8
Quercus bicolor	Bare root	91.5	87.2	80.9	80.9	78.7	80.9	100.0	97.4	97.4	92.3	92.3	89.7	95.1	58.5	26.8	14.6	14.6	17.1	89.3	62.7	58.7	53.3	44.0	42.7
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	100.0	100.0	86.1	58.3	33.3	30.6	30.6	98.7	96.1	94.7	92.1	75.0	73.7
Quercus bicolor	Tubeling	72.3	57.4	51.1	48.9	44.7	44.7	80.5	78.0	73.2	65.9	65.9	61.0	79.5	31.8	6.8	0.0	2.3	0.0	90.7	78.7	74.7	66.7	60.0	57.3
Quercus palustris	Bare root	86.7	77.8	73.3	71.1	71.1	71.1	97.2	91.7	86.1	77.8	80.6	77.8	87.8	51.0	4.1	2.0	2.0	4.1	96.1	67.1	55.3	53.9	50.0	50.0
Quercus palustris	Gallon	100.0	100.0	100.0	100.0	100.0	97.2	100.0	100.0	95.0	95.0	95.0	95.0	97.6	73.8	28.6	14.3	19.0	4.8	98.7	89.5	85.5	84.2	76.3	76.3
Quercus palustris	Tubeling	51.6	38.7	25.8	22.6	22.6	16.1	71.9	56.3	50.0	50.0	46.9	43.8	74.3	20.0	8.6	0.0	0.0	0.0	88.5	73.1	65.4	60.3	56.4	57.7
Quercus phellos	Bare root	73.6	64.2	50.9	49.1	47.2	45.3	78.7	73.8	63.9	60.7	57.4	55.7	69.2	32.3	9.2	3.1	1.5	1.5	87.0	36.4	31.2	22.1	11.7	16.9
Quercus phellos	Gallon	100.0	97.1	91.4	88.6	88.6	85.7	100.0	97.1	94.1	94.1	94.1	94.1	100.0	66.7	38.5	25.6	33.3	17.9	92.2	83.1	79.2	77.9	70.1	66.2
Quercus phellos	Tubeling NO SOIL	58.3	33.3	33.3	29.2	29.2	25.0	68.9	62.2	60.0	53.3	53.3	51.1	50.0	10.7	0.0	0.0	0.0	0.0	67.1	18.4	7.9	6.6	7.9	6.6
Salix nigra	Bare root	21.9	3.1	0.0	0.0	0.0	0.0	67.4	41.9	30.2	30.2	27.9	27.9	90.0	90.0	85.0	87.5	85.0	85.0	75.0	38.2	34.2	30.3	28.9	31.6
Salix nigra	Gallon	97.3	97.3	91.9	91.9	91.9	89.2	94.7	94.7	92.1	92.1	89.5	86.8	94.7	94.7	84.2	94.7	94.7	94.7	100.0	72.4	71.1	68.4	67.1	67.1
Salix nigra	Tubeling NO SOIL	55.0	47.5	35.0	35.0	32.5	30.0	73.6	49.1	35.8	30.2	28.3	28.3	91.7	83.3	83.3	80.6	75.0	77.8	89.3	64.0	61.3	58.7	49.3	48.0
	Average	72.6	66.0	62.7	61.6	61.0	59.7	80.9	74.6	70.6	68.3	67.5	66.4	82.4	60.7	38.2	32.6	32.4	30.7	86.4	59.6	54.1	51.1	44.6	43.9

Height Growth

Changes in tree height were compared to the 10% increase in height per year proposed ecological performance standard.

Mesocosm

There were four species/stocktype combinations that did not meet the required >10% height increase in 2009 in the Ambient cell; however, in 2010, 2011, 2012 and 2013 all species/stocktype achieved the required >10% increase in height (Table 3). In 2014, *Q. phellos* tubeling did not exceed the 10% increase.

In the Saturated cell 10 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 and 2014. In the Flooded cell 8 species/stocktype combinations had <10% increase in height in 2009, 15 in 2010, 18 in 2011, 9 in 2012 and 2013, and 14 in 2014.

The general trend of height growth rates in the Ambient cell and Saturated cell is the gallon stocktype initially has a very high growth rate followed by decreasing growth rates as time progresses. However, for the bare root and tubeling stocktype there is a peak in height growth rate in the second growing season in the Ambient cell and a peak in the third growing season in the Saturated cell. This suggests that the bare root and tubeling stocktype need additional time to acclimate to the environmental conditions compared to the gallon stocktype.

Field

In the Field sites, 19 species/stocktype combinations did not meet the >10% requirement in 2009, with 11 not meeting the requirement in 2010, and 2 not meeting the requirement in 2011. In 2012 all species/stocktypes met the >10% increase in height. However, in 2013 1 species/stocktype combination did not meet the requirement and in 2014 this number increased to 5 species/stocktype combinations (Table 3), suggesting a slowing of growth rate in recent years.

Average growth rate peaked in 2011 for all combinations (35.9%) with the average percent change in height decreasing in each subsequent year (31.1% in 2012, 26.2% in 2013, and 23.2% in 2014). Die back occurred in multiple species/stocktypes the first two years of the study.

Table 3. Average percent change in height per year for 2009 through 2014. Percentage represents change over one year. Red indicates dieback and orange indicates <10% increase. NA represents combinations that had 0% survival.

		Ambient						Saturated						Flooded						Field					
Species	Stocktype	2009 % Height	2010 % Height	2011 % Height	2012 % Height	2013 % Height	2014 % Height	2009 % Height	2010 % Height	2011 % Height	2012 % Height	2013 % Height	2014 % Height	2009 % Height	2010 % Height	2011 % Height	2012 % Height	2013 % Height	2014 % Height	2009 % Height	2010 % Height	2011 % Height	2012 % Height	2013 % Height	2014 % Height
Betula nigra	Bare root	98.9	173.3	132.9	49.4	31.3	29.5	14.1	84.2	126.1	60.7	57.7	33.3	25.6	6.6	-30.8	97.9	49.1	34.3	-9.5	35.4	24.7	44.2	51.3	14.3
Betula nigra	Gallon	461.0	85.5	60.4	46.8	31.8	35.3	575.7	34.3	61.7	87.1	35.2	32.8	29.4	5.0	17.0	-8.6	24.0	18.5	-3.1	-13.9	3.2	15.9	23.8	26.8
Betula nigra	Tubeling	74.0	129.5	144.3	62.9	51.0	32.4	95.7	105.1	122.5	59.5	64.4	34.4	14.8	13.3	-10.5	9.9	37.1	25.5	9.4	25.2	31.0	30.6	43.6	34.6
Liquidambar styraciflua	Bare root	95.3	163.8	104.5	46.7	40.7	27.6	-30.8	74.3	115.8	81.1	60.5	33.6	-7.7	5.5	-3.7	5.6	18.1	7.0	-5.9	-15.1	44.6	44.8	28.9	8.9
Liquidambar styraciflua	Gallon	354.5	87.2	70.9	39.3	34.5	21.6	200.2	54.8	58.9	57.7	52.6	28.7	37.3	-1.1	-4.5	1.8	-11.6	0.6	4.9	-17.3	75.9	25.4	23.2	8.4
Liquidambar styraciflua	Tubeling	40.3	216.1	123.0	56.3	37.8	27.9	-91.1	98.9	143.6	56.4	72.1	43.2	32.6	19.5	3.2	19.6	20.8	18.2	22.7	79.9	44.9	35.3	82.8	19.4
Platanus occidentalis	Bare root	262.8	317.5	128.2	51.7	37.7	28.8	4.4	94.1	184.5	101.4	91.0	NA	-50.5	-25.6	NA	NA	NA	NA	-24.4	26.7	37.6	38.4	19.2	9.8
Platanus occidentalis	Gallon	538.5	106.2	90.2	45.3	35.0	17.6	250.4	5.6	66.0	22.5	49.1	21.5	-40.1	-30.0	-22.3	-4.9	7.8	-8.0	-13.2	-18.7	21.4	27.8	12.0	91.7
Platanus occidentalis	Tubeling NO SOIL	273.9	243.1	92.6	44.7	32.7	33.2	26.4	61.1	180.5	65.7	52.5	33.9	-46.9	10.2	0.0	-53.6	12.5	NA	-19.0	5.9	47.5	46.4	31.8	11.2
Quercus bicolor	Bare root	90.8	16.7	45.8	42.4	36.4	13.0	117.9	16.6	55.2	38.1	33.9	38.8	1.9	-17.1	-36.9	20.5	11.6	0.7	3.5	-17.2	13.7	30.2	29.2	42.8
Quercus bicolor	Gallon	87.6	87.3	55.6	48.9	35.9	16.2	5.0	32.0	69.1	28.3	54.4	24.3	20.4	-3.3	-3.1	-2.8	-8.6	-9.3	9.4	7.5	18.8	17.6	11.6	8.0
Quercus bicolor	Tubeling	-82.4	32.2	76.7	68.2	38.6	13.8	-114.1	11.8	81.4	45.5	47.2	33.8	-6.7	-11.1	-15.9	15.0	-1.0	-38.8	4.2	54.9	37.5	24.3	24.5	16.0
Quercus palustris	Bare root	74.0	38.8	64.5	64.9	34.0	25.6	-74.6	13.8	95.0	47.8	33.4	33.5	-8.6	-31.1	-5.3	11.0	10.2	10.8	-1.2	-13.3	36.3	38.8	22.4	19.1
Quercus palustris	Gallon	260.4	22.7	37.9	47.8	35.2	18.3	233.6	3.9	33.2	27.6	31.8	31.3	3.5	-8.3	-44.7	3.5	-22.1	-12.8	3.5	11.9	1.6	26.6	9.0	25.3
Quercus palustris	Tubeling	-90.4	72.9	93.4	45.1	17.9	25.9	-114.0	56.0	70.5	78.2	28.4	23.2	-8.1	4.5	-12.9	8.0	9.1	NA	-25.1	74.6	53.5	23.8	17.5	21.4
Quercus phellos	Bare root	8.9	32.6	73.6	69.7	44.2	13.6	-23.1	47.8	91.8	58.8	42.5	26.8	-22.0	-25.0	-4.7	67.2	10.0	1.7	-16.5	-39.3	30.2	33.8	42.9	35.9
Quercus phellos	Gallon	472.1	41.2	40.7	32.6	71.7	20.7	424.0	7.7	32.9	25.8	77.0	26.6	1.8	-9.0	-15.2	-16.1	-13.7	-9.5	11.6	4.8	29.1	10.6	13.5	14.4
Quercus phellos	Tubeling NO SOIL	14.6	98.9	57.4	73.1	42.2	4.3	-55.2	67.3	81.5	59.7	48.2	32.3	-60.5	-39.4	NA	NA	NA	NA	-31.8	-55.6	117.0	37.4	17.0	40.4
Salix nigra	Bare root	-50.2	137.2	80.3	104.2	58.7	NA	36.4	154.9	135.7	73.1	39.0	27.4	36.4	71.8	21.4	25.5	23.9	13.8	0.7	60.8	37.0	34.3	13.3	18.8
Salix nigra	Gallon	457.1	22.5	48.1	43.6	30.5	19.4	237.4	0.3	89.0	45.6	28.2	18.0	15.2	1.5	-3.7	2.8	11.2	3.9	7.1	2.4	21.0	29.2	15.0	8.7
Salix nigra	Tubeling NO SOIL	174.4	98.9	125.0	62.1	34.8	40.0	-2.9	34.6	112.1	77.3	55.5	28.2	19.8	62.4	38.3	5.8	31.4	50.8	1.1	18.8	27.1	37.8	18.7	11.5
	Average	172.2	105.9	83.1	54.6	38.7	23.2	81.7	50.4	95.6	57.1	50.2	30.3	-0.6	0.0	-7.1	10.9	11.6	6.3	-3.4	10.4	35.9	31.1	26.2	23.2

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 mean canopy diameter of trees 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.

Mesocosm

No species/stocktype combinations exceeded 150 cm in diameter in the Flooded cell after 6 years (Table 4). In the Ambient cell all of the species and stocktype combinations exceeded 150 cm in canopy diameter by 2013. However, in 2014, the average canopy diameter of *Q. palustris* tubeling did not exceed 150 cm in the Ambient cell. In the Saturated cell all but 2 species/stocktype combinations (*Q. bicolor* bare root and tubeling) did not exceed 150 cm.

Field

No species/stocktype combinations exceeded 150 cm in diameter in the Field sites in the first five years of the study. In 2014 *S. nigra* gallon was the only species/stocktype combination to exceed 150 cm in diameter in the Field study (Table 4).

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. Blanks represent combinations that had no trees greater than 100cm.

		Ambient						Saturated						Flooded						Field					
Species	**Stocktype**	**2009 CD (cm)**	**2010 CD (cm)**	**2011 CD (cm)**	**2012 CD (cm)**	**2013 CD (cm)**	**2014 CD (cm)**	**2009 CD (cm)**	**2010 CD (cm)**	**2011 CD (cm)**	**2012 CD (cm)**	**2013 CD (cm)**	**2014 CD (cm)**	**2009 CD (cm)**	**2010 CD (cm)**	**2011 CD (cm)**	**2012 CD (cm)**	**2013 CD (cm)**	**2014 CD (cm)**	**2009 CD (cm)**	**2010 CD (cm)**	**2011 CD (cm)**	**2012 CD (cm)**	**2013 CD (cm)**	**2014 CD (cm)**
Betula nigra	Bare root		122.3	288.9	392.7	461.7	541.5		73.2	167.3	259.2	369.2	434.4				105.3	93.7	149.9	75.2		42.1	46.9	57.5	68.1
Betula nigra	Gallon	65.7	190.0	360.4	487.2	625.3	714.5	56.3	112.2	247.7	356.1	456.3	524.9	59.2	57.4	51.3	83.7	90.1	107.4	75.9	77.7	62.2	81.4	99.9	129.1
Betula nigra	Tubeling		126.6	230.3	364.1	443.5	526.3		72.3	173.0	283.9	397.3	477.9			33.0	114.0	74.9	94.0		47.3	42.8	59.9	69.8	92.6
Liquidambar styraciflua	Bare root		104.8	179.2	255.4	341.4	361.1		71.8	107.7	172.4	255.3	291.8					84.3	81.2			37.0	35.4	42.9	62.1
Liquidambar styraciflua	Gallon	55.6	115.8	183.9	255.1	318.8	342.4	34.8	68.8	139.6	203.0	265.7	301.5	45.0	45.6	43.4	40.1	48.5	67.6	28.6	38.1	46.0	52.2	69.6	86.4
Liquidambar styraciflua	Tubeling		114.8	161.3	214.8	293.6	275.7		62.3	108.5	158.8	241.6	286.0					40.3	68.7				47.2	66.9	71.8
Platanus occidentalis	Bare root		109.1	257.4	377.8	524.3	580.1		43.7	66.8	150.2	227.9										25.0	45.0	48.3	56.3
Platanus occidentalis	Gallon	50.7	125.8	224.9	318.7	409.2	433.0	31.2	60.1	137.1	196.6	264.8	299.1	30.7	26.1	18.8		57.3		33.3	40.3	39.6	56.9	74.3	103.6
Platanus occidentalis	Tubeling NO SOIL	39.0	131.3	291.6	415.4	559.2	656.8		48.8	116.0	225.8	353.2	413.7								19.0	26.6	33.7	50.0	62.8
Quercus bicolor	Bare root		80.8	125.3	160.9	188.0	196.4			114.2	105.4	135.3	144.4					87.7	75.7				58.3	59.1	75.7
Quercus bicolor	Gallon		75.7	124.0	150.7	203.4	209.6		54.8	97.0	107.2	156.1	150.5				70.3	118.3		45.5	47.1	47.0	55.7	68.4	79.4
Quercus bicolor	Tubeling		69.3	107.4	139.7	174.7	193.2			78.1	87.1	109.8	122.6								17.0			62.0	82.4
Quercus palustris	Bare root		70.3	114.2	158.6	201.5	201.0			84.6	110.0	143.0	171.0										46.0		57.3
Quercus palustris	Gallon	65.0	97.1	139.9	195.3	235.2	249.7	65.6	76.3	109.8	162.4	180.9	196.9	66.8	62.0	70.3	82.2	116.7	130.3	47.5	48.7	49.8	51.4	59.6	70.7
Quercus palustris	Tubeling			87.7	122.3	159.0	142.6			88.7	100.4	117.2	152.7								29.7			40.6	56.7
Quercus phellos	Bare root		97.0	131.7	143.2	181.1	181.3		27.0	95.2	121.4	160.7	195.7	76.2	73.3		64.9							22.0	51.4
Quercus phellos	Gallon	69.9	103.9	174.0	224.9	266.9	304.4	64.7	88.1	150.3	190.2	231.5	269.6	68.0	69.5	61.2		88.6	104.0	49.1	57.2	47.0	55.4	77.5	91.5
Quercus phellos	Tubeling NO SOIL	68.8	99.0	139.9	167.1	183.4	186.2			105.2	115.6	135.6	174.5												
Salix nigra	Bare root		97.3	291.7	235.5	281.7			83.1	228.0	320.3	363.7	408.3		74.8	80.0	79.0	104.2	120.3	14.0	54.1	60.4	71.2	90.8	116.7
Salix nigra	Gallon	69.8	166.7	297.1	337.3	362.6	367.6	44.9	91.2	201.3	290.4	327.4	350.5	55.2	98.2	112.2	97.1	116.3	124.6	49.8	66.8	82.6	113.9	149.0	177.0
Salix nigra	Tubeling NO SOIL	39.3	133.4	206.1	292.9	349.2	400.8		67.3	208.6	252.7	336.9	375.5		79.6	95.4	78.1	94.1	113.0	35.4	51.1	58.2	85.7	105.6	122.2
	Average	58.2	111.6	196.0	257.6	322.1	353.2	49.6	68.8	134.5	189.0	249.0	287.1	57.3	65.2	62.9	81.5	86.8	103.1	45.4	45.7	47.6	58.6	69.1	85.7

Beaver Damage at Field Site

From the beginning of the study to present, no beaver damage to planted trees was observed at Phases I or II. In May of 2014, beaver damage to planted trees was observed for the first time at Phase III. During collection of morphometric data in August of 2014, note was taken of obvious tree damage caused by beaver herbivory, which included girdling and stem removal. As of August of 2014, 148 of the 607 (24.4%) trees which were alive at Phase III in August of 2013 experienced some form of beaver damage. Of the 39 trees which died between August 2013 and 2014, 6 (15.4%) exhibited beaver damage.

The proportion of beaver damage to live trees was quantified within species/stocktype combinations (Figure 6). The most impacted species were *S. nigra* (50%), *L. styraciflua* (34.8%) and *Q. phellos* (32.1%). The least impacted species was *P. occidentalis* (1.5%). The gallon stocktype was the most impacted (36.3%) while the bare-root stocktype was least impacted (14.9%).

A paired-samples t-test indicated average basal diameter (BD) within species/stocktype combinations were significantly smaller (mean = 25.7, standard deviation = 15.4) than the average BD of beaver impacted trees (mean = 28.5, standard deviation = 16.4) (p = 0.007). This analysis revealed beaver impacted trees had larger BDs than the undisturbed trees of the corresponding species/stocktype groups. No significant relationships were observed between tree height or stem volume and beaver impact.

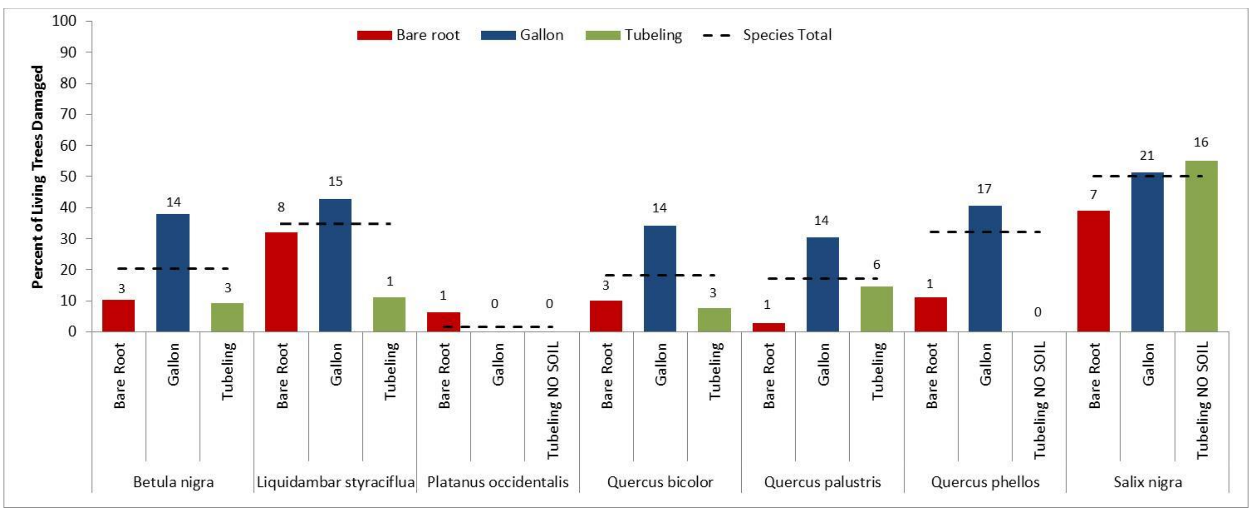

Figure 6. Percent of living trees at Phase III of the Field sites exhibiting beaver damage in August of 2014. Bars represent the percentage of living trees that were damaged by species/stocktype combination. Dashed lines represent the total percentage of trees damaged by species. Numbers above bars represent number of trees damaged.

Economic Analysis

In order to determine the cost required to insure adequate stem density, the plant material cost, installation cost, and miscellaneous costs (Table 5) were combined with the percent survival after six years (Table 6).

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

Table 5. 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 6. Percent survival represents the survival five 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. NA's and blanks represent combinations with 0% survival after six years.

						Ambient			Saturated			Flooded			Field Study		
Species	Stocktype	Price ($/Tree)	Installation Cost	Misc. Cost	Total Cost	% Survival 2014	Initial Density Required	Cost per ha	% Survival 2014	Initial Density Required	Cost per ha	% Survival 2014	Initial Density Required	Cost per ha	% Survival 2014	Initial Density Required	Cost per ha
Betula nigra	Bare root	0.65	1.00	0.25	1.90	33.3	2970	$5,643	55.8	1774	$3,370	9.4	10494	$19,939	40.8	2427	$4,611
Betula nigra	Gallon	3.25	5.00	2.00	10.25	100.0	990	$10,148	97.2	1018	$10,437	78.4	1263	$12,947	65.3	1515	$15,532
Betula nigra	Tubeling	1	1.75	1.25	4.00	25.8	3836	$15,345	68.8	1440	$5,760	66.7	1485	$5,940	43.4	2280	$9,120
Liquidambar styraciflua	Bare root	0.65	1.00	0.25	1.90	68.3	1450	$2,754	69.4	1426	$2,709	28.6	3465	$6,584	27.6	3583	$6,807
Liquidambar styraciflua	Gallon	3.25	5.00	2.00	10.25	92.3	1072	$10,993	100.0	990	$10,148	70.3	1409	$14,441	42.9	2310	$23,678
Liquidambar styraciflua	Tubeling	1	1.75	1.25	4.00	13.9	7128	$28,512	35.0	2829	$11,314	47.1	2104	$8,415	13.2	7524	$30,096
Platanus occidentalis	Bare root	0.56	1.00	0.25	1.81	55.8	1774	$3,210	0.0		NA	0.0		NA	19.7	5016	$9,079
Platanus occidentalis	Gallon	3.25	5.00	2.00	10.25	82.1	1207	$12,367	92.1	1075	$11,017	10.8	9158	$93,864	33.3	2970	$30,443
Platanus occidentalis	Tubeling NO SOIL	1	1.75	1.25	4.00	96.7	1024	$4,097	64.5	1535	$6,138	0.0		NA	40.8	2427	$9,708
Quercus bicolor	Bare root	0.65	1.00	0.25	1.90	80.9	1224	$2,327	89.7	1103	$2,096	17.1	5799	$11,017	42.7	2320	$4,409
Quercus bicolor	Gallon	3.25	5.00	2.00	10.25	100.0	990	$10,148	100.0	990	$10,148	30.6	3240	$33,210	73.7	1344	$13,772
Quercus bicolor	Tubeling	1	1.75	1.25	4.00	44.7	2216	$8,863	61.0	1624	$6,494	0.0		NA	57.3	1727	$6,907
Quercus palustris	Bare root	0.65	1.00	0.25	1.90	71.1	1392	$2,645	77.8	1273	$2,418	4.1	24255	$46,085	50.0	1980	$3,762
Quercus palustris	Gallon	3.25	5.00	2.00	10.25	97.2	1018	$10,437	95.0	1042	$10,682	4.8	20790	$213,098	76.3	1297	$13,297
Quercus palustris	Tubeling	1	1.75	1.25	4.00	16.1	6138	$24,552	43.8	2263	$9,051	0.0		NA	57.7	1716	$6,864
Quercus phellos	Bare root	0.65	1.00	0.25	1.90	45.3	2186	$4,154	55.7	1776	$3,375	1.5	64348	$122,262	16.9	5864	$11,141
Quercus phellos	Gallon	3.25	5.00	2.00	10.25	85.7	1155	$11,839	94.1	1052	$10,782	17.9	5516	$56,536	66.2	1495	$15,321
Quercus phellos	Tubeling NO SOIL	1	1.75	1.25	4.00	25.0	3960	$15,840	51.1	1937	$7,748	0.0		NA	6.6	15048	$60,192
Salix nigra	Bare root	0.48	1.00	0.25	1.73	0.0		NA	27.9	3547	$6,137	85.0	1165	$2,015	31.6	3135	$5,424
Salix nigra	Gallon	7.95	5.00	2.00	14.95	89.2	1110	$16,595	86.8	1140	$17,043	94.7	1045	$15,623	67.1	1475	$22,056
Salix nigra	Tubeling NO SOIL	1	1.75	1.25	4.00	30.0	3300	$13,200	28.3	3498	$13,992	77.8	1273	$5,091	48.0	2063	$8,250

Cost per ha
<5000
5000-10000
10000-15000
>15000

Species/Stocktype Ranking

Two ranking strategies for addressing Objective 1 were investigated. The first calculates and average rank for the 21 species/stocktype combinations based on survival, economic, and all morphological variables for all six years (Table 7). This method gives more weight to the morphological and survival parameters compared to the economic values. In order to increase the importance of the economic values, the second method only uses morphological, survival and economic data from 2014 (Table 8). Both of these methods attempt to minimize cost while maximizing ecological performance but do conceal the variations in the data.

When six years of both Mesocosm and Field studies are combined, the optimum species/stocktype combination was *B. nigra* gallon (Table 7). The top three combinations are the gallon stocktype and primary successional species. The remaining primary successional species, *P. occidentalis* gallon did very poorly in the Flooded cell and Field study, having an overall ranking of 11th. In the top ten species/stocktype combination only three are oak species grown in gallon containers. This suggests that primary successional species (excluding *P. occidentalis*) and the secondary successional species grown in gallon containers are appropriate for planting in restored forested wetlands.

Table 7. The ranking of all species and stocktype in the Mesocosm, Field and Overall based on six years of survival, morphological and economic values.

Species	Stocktype	Overall Rank	Ideal Rank	Saturated Rank	Flooded Rank	Field Rank
Betula nigra	Gallon	1	1	1	2	2
Salix nigra	Gallon	2	6	11	4	1
Liquidambar styraciflua	Gallon	3	5	2	5	8
Betula nigra	Tubeling	4	12	3	6	7
Quercus phellos	Gallon	5	7	4	9	3
Salix nigra	Tubeling NO SOIL	6	13	15	3	5
Quercus bicolor	Gallon	7	8.5	9	7	6
Quercus palustris	Gallon	8	8.5	10	13	4
Betula nigra	Bare root	9	11	7	10	13
Salix nigra	Bare root	10	20	13	1	10
Platanus occidentalis	Tubeling NO SOIL	11	2	6	19	12
Liquidambar styraciflua	Bare root	12	10	8	12	18
Platanus occidentalis	Gallon	13	4	5	14	16.5
Quercus bicolor	Bare root	14	15	12	11	11
Liquidambar styraciflua	Tubeling	15	17	17.5	8	16.5
Quercus palustris	Bare root	16	14	14	16	15
Quercus bicolor	Tubeling	17	18	19	17	9
Quercus phellos	Bare root	18	16	16	15	20
Platanus occidentalis	Bare root	19	3	20	21	19
Quercus palustris	Tubeling	20	21	21	18	14
Quercus phellos	Tubeling NO SOIL	21	19	17.5	20	21

When investigating ranking combination using only year six data, the top combination remains *B. nigra* gallon (Table 8). However, ranks 2-7 are bare-root or tubeling stocktypes and the gallon stocktypes decrease in ranking. The primary species continue to be ranked higher than the secondary species.

Table 8. The ranking of all species and stocktype in the Mesocosm, Field and Overall based only on year six survival, morphological and economic values.

Species	Stocktype	Overall Rank	Ideal Rank	Saturated Rank	Flooded Rank	Field Rank
Betula nigra	Gallon	1	1.5	2	3	1
Betula nigra	Tubeling	2	11	1	4.5	3
Betula nigra	Bare root	3	4.5	5.5	6.5	12
Salix nigra	Tubeling NO SOIL	4	8	19	1	5.5
Quercus bicolor	Bare root	5	15	3.5	10	2
Liquidambar styraciflua	Bare root	6	4.5	5.5	8	17
Quercus palustris	Bare root	7.5	6	7.5	13	7.5
Salix nigra	Gallon	7.5	14	18	4.5	9.5
Liquidambar styraciflua	Gallon	9	7	7.5	9	18
Platanus occidentalis	Tubeling NO SOIL	10.5	1.5	3.5	19.5	15
Quercus palustris	Gallon	10.5	9.5	9	15	4
Quercus phellos	Gallon	12.5	12.5	14.5	11	9.5
Salix nigra	Bare root	12.5	21	10	2	5.5
Quercus bicolor	Gallon	14	9.5	12.5	12	14
Platanus occidentalis	Gallon	15	12.5	16.5	14	11
Liquidambar styraciflua	Tubeling	16	18	12.5	6.5	19
Quercus phellos	Bare root	17	16	14.5	16	16
Quercus bicolor	Tubeling	18	17	11	17	13
Platanus occidentalis	Bare root	19	3	21	19.5	20
Quercus palustris	Tubeling	20	19	20	19.5	7.5
Quercus phellos	Tubeling NO SOIL	21	20	16.5	19.5	21

When comparing the two methods of ranking the species and successional group rankings remain very similar, however, the average overall rankings of the stocktypes change dramatically (Table 9). Using only data from year six the gallon and bare-root have very similar rankings whereas, using data from all six years the gallon stocktype has higher rankings than the bare-root. The increased similarity in rankings between the bare-root and gallon stocktypes using the second method is due to the increased weighting of planting costs and the increased performance of bare-root stocktypes through time. The gallon stocktype had better performance directly following outplanting which is incorporated in the first method.

Table 9. Average overall ranking of species, stocktype, and successional groups using all six years of data (left) and just data from year six (right).

Species	Average Overall Rank
Betula nigra	4.7
Salix nigra	6.0
Liquidambar styraciflua	10.0
Quercus bicolor	12.7
Platanus occidentalis	14.3
Quercus palustris	14.7
Quercus phellos	14.7
Stocktype	**Average Overall Rank**
Gallon	5.6
Tubeling	13.4
Bare-root	14.0
Successional Groups	**Average Overall Rank**
Primary	8.8
Secondary	14.0

Species	Average Overall Rank
Betula nigra	2.0
Salix nigra	8.0
Liquidambar styraciflua	10.3
Quercus bicolor	12.3
Quercus palustris	12.7
Platanus occidentalis	14.8
Quercus phellos	16.8
Stocktype	**Average Overall Rank**
Gallon	9.9
Bare-root	10.0
Tubeling	13.1
Successional Groups	**Average Overall Rank**
Primary	8.8
Secondary	13.9

<u>Objective 2</u>

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 (Biomass Estimation Models).
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.

Biomass Estimation Models

Goal one was addressed in this study by developing biomass estimation models (BEM). These models have been constructed for trees using the following general equation (Eq.1) (power or power-law equation) and/or transformations of this equation (Chojnacky et al. 2014, Jenkins et al. 2003, Tefler 1969, Ter-Mikaelian and Korzukhin 1997, Tritton and Hornbeck 1982, Whittaker and Woodwell 1968, Xiao and Ceulemans 2004).

$$Y = aX^b + \varepsilon \qquad \text{(Eq. 1)}$$

Y = biomass (response or dependent variable)
a = model estimated parameter (normalization or proportionality constant or intercept)
X = tree dimension variable (predictor or independent variable)
b = model estimated parameter (exponent)
ε = Error term (Random normally distributed additive error term with constant variance)

These equations are developed and used for a variety of purposes including; predicting biomass of standing trees non-destructively, estimating carbon accumulation, allocation and fluxes, and examining relationships and changes among biological traits (allometry or dimensional analysis).

Since the relationship between morphology and biomass varies through time as a result of species and environmental conditions, above-ground biomass (AGB) and below-ground biomass (BGB) samples were taken in the winter of 2010-2011 and then AGB was sampled from additional trees in late winter 2014.

Table 10. Range of measured morphological characteristics

Primary Successional Species	2011 N	2014 N	Total N	Equivalent Basal Diameter (cm)	Height (cm)	Canopy Diameter (cm)	BGB (kg)	AGB (kg)	Total Biomass (kg)
Betula nigra	43	33	76	0.4-34.3	35-1020	8-775	0.001-45.57	0.001-143.82	0.003-189.39
Liquidambar styraciflua	49	34	83	0.2-12.3	4-750	1-423	0.002-26.64	0.001-23.56	0.003-50.2
Platanus occidentalis	53	36	89	0.4-24.4	4-1110	1-753	0.001-144.59	0.001-128.44	0.002-273.03
Salix nigra	50	37	87	0.4-22.1	8-1155	2-535	0.002-10.32	0.002-53.56	0.004-63.88
Secondary Successional Species									
Quercus bicolor	47	27	74	0.3-7.5	9-420	4-293	0.003-9.86	0.002-5.68	0.005-15.54
Quercus palustris	52	28	80	0.3-8	14-710	2-325	0.003-5.23	0.001-7.16	0.005-12.39
Quercus phellos	52	26	78	0.3-10.5	19-600	1-343	0.002-4.41	0.001-15.46	0.003-19.87
ALL SP	346	221	567	0.2-34.3	4-1155	1-775	0.001-144.59	0.001-143.82	0.002-273.03

A random subsample of trees (n=338) were removed from the Mesocosm site in the winter of 2010-2011 to measure ABG and BGB biomass (Table 10). The complete above- and below-ground portions of the trees were separated and placed in individual paper bags. Sampling occurred after leaf senescence and leaf biomass was not measured. Therefore, BGB refers only to roots and AGB refers to stems and branches. All trees were solar dried on-site at ~50 C in re-purposed greenhouses until constant weight was obtained. The trees were weighed at the end of the summer in 2011.

A random subsample of trees (n=222) were removed from the Mesocosm site in early spring of 2014 to measure woody above-ground biomass (Table 10). The complete above-ground portion of the trees was removed and either cut into smaller portions and wrapped in plastic or dried as whole trees in same repurposed greenhouses as above. Sampling occurred prior to leaf emergence and leaf biomass was not measured. Trees were weighed mid-summer in 2014. The below-ground biomass of the 2014 samples were estimated based on the relationship between above- and below-ground biomass for the 2011 samples.

Table 11. Results of fitting Eq. 1 ($Y=aX^b + \varepsilon$). Y=Total dry biomass (excluding leaves) (kg). X=average basal diameter (cm) for the 2011 and 2014 samples combined.

Primary Successional Species	a	a STERR	b	b STERR	Standard Error of the Regression
Betula nigra	0.0316777	0.0048558	2.4419198	0.0665102	0.6673714
Liquidambar styraciflua	0.0317770	0.0100781	2.7512410	0.1492996	0.9083254
Platanus occidentalis	0.0275311	0.0027393	2.7888479	0.0494827	0.5223591
Salix nigra	0.0290348	0.0074763	2.5190495	0.0988290	0.9108000
Secondary Successional Species					
Quercus bicolor	0.0472973	0.0072147	2.7351962	0.1134003	0.5710256
Quercus palustris	0.0472934	0.0041728	2.5024261	0.1331602	1.0157480
Quercus phellos	0.0554955	0.0069351	2.4554801	0.1719241	1.8912760

The results of developing the BEM for the primary successional species (Figure 7) and secondary successional species (Figure 8) suggest that the power-law equation is appropriate for describing the relationship between average basal diameter and total biomass (Table 11Table 11). In future publications the developed BEM will be applied to all trees planted in the Mesocosm and Field study across all years to determine the amount of biomass produced by each species. This will help determine how each species is contributing to returning the lost ecological function of woody productivity and carbon sequestration.

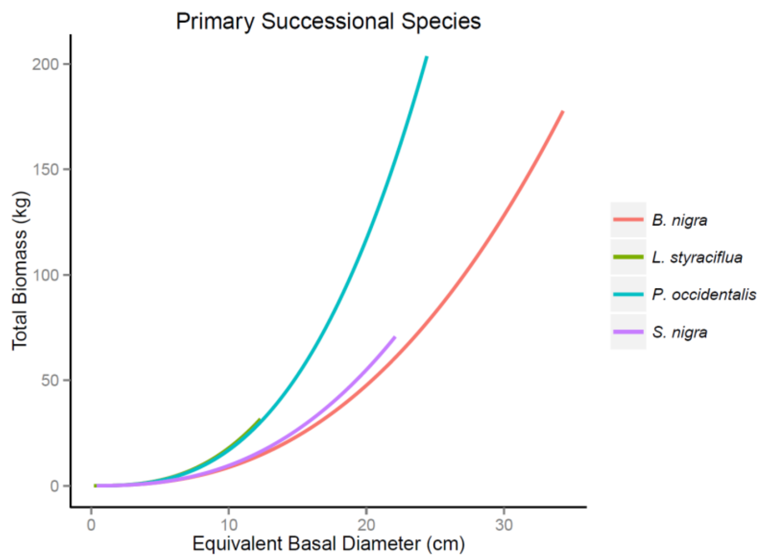

Figure 7. Relationship between basal diameter and total biomass of the primary successional species

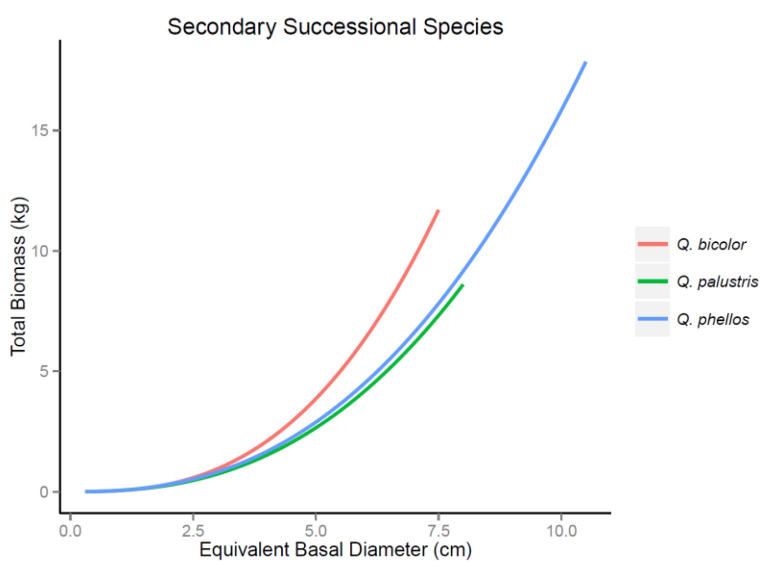

Figure 8. Relationship between basal diameter and total biomass of the primary successional species

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 achieve 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.

<u>Survival</u>

Following the sixth growing season survival has stabilized in the Ambient and Saturated cells while it continues to decrease in the Flooded cell and Field study. This suggests that after six years hydrologic and competitive stressors are influencing planted trees while the effect of transplanting has diminished. Across the Mesocosm cells and Field study the tubeling stocktype and to some extent the bare root stocktype have poor survival (with some combinations reaching 0% survival). The gallon stocktype only has reduced survival in the harsher environmental conditions for particular species (*Quercus* spp. and *P. occidentalis*).

In the flooded cell and Field study 15 and 16 species/stocktype combinations respectively fell below the threshold to ensure 400 stems/acre based on the initial planting density in this study after six years (58.8%). This suggests that the initial planting density in these harsh environments should be increased to greater than 1230 stems/acre (~6 ft spacing) and 3825 stems/acre (~3 ft spacing) in the Field study and Flooded cell respectively.

Selection of woody species and stocktypes appropriate to the environmental conditions and planting at sufficient densities is vital to not only meeting regulatory requirements but ensuring that the ecological structure and functions provided by trees (habitat, primary productivity, carbon cycling etc.) are returned to the landscape. Based on the results of survival analysis the gallon stocktype and primary successional species (excluding *P. occidentalis*) are better choices across a range of habitats to ensure adequate establishment of trees that will contribute to the ecological structure and functions of restored/created wetlands. Other research has found that larger containerized stocktype typically have increased survival compared to small bare-root stocktypes (Burdett et al. 1984, South et al. 2005).

<u>Height Growth</u>

After woody vegetation is established, growth is the next important factor that indicates ecological structure and functioning is returning. A 10% percent increase in height per year has been selected as an ecological performance standard for restored/created wetland mitigation banks and is currently required for some projects. An analysis of the height growth for this study indicates that in less environmentally stressful conditions (Ambient and Saturated cells), most species/stocktype combinations are able to exceed this requirement. However, in environmental conditions similar to (Field study) or harsher than (Flooded cell) those found in recently restored wetlands, most species/stocktypes do not meet this requirement or may take 2+ years to reach this goal. In particular, the *Quercus* spp. in the Flooded cell rarely exceeded this goal, while the

B. nigra and *S. nigra* were able to reach this target, suggesting that these species may be more appropriate to plant in stressful hydrologic conditions because of their particular adaptations. In the Field study, very few species/stocktype combinations exceeded 10% increase in height the first two years but most were able to exceed or nearly exceed this goal in the subsequent four years. This suggests that it may take additional time to overcome transplant shock in restored wetland conditions. Additionally, the gallon stocktype typically had greater initial growth rates which may be important where herbaceous vegetation competition is expected. Overall, height growth is a good indicator that ecological structure and functioning is returning and larger stocktype and primary successional species are able to achieve this goal in harsher environmental conditions.

Canopy Closure

In addition to height growth, canopy closure is a good indicator that ecological structure and functions, in particular plant and animal habitat, are returning. The ecological performance standard for restored/created wetlands is 30% canopy closure of trees >100 cm. This corresponds to 150 cm canopy diameter for the planting density in this study (assuming 100% survival). The results from the canopy closure analysis suggest that primary successional species may reach 30% canopy closure earlier than the secondary successional species. In the Flooded cell none of the species/stocktype combinations exceeded 150 cm in canopy diameter, suggesting that hydrologic stress and/or herbaceous competition may reduce height and canopy growth. Only the *B. nigra* and *S. nigra* are approaching a canopy diameter of 150 cm in these locations. In the Field study, average canopy of *S. nigra* gallon exceeded 150 cm in 2014. This suggests that *S. nigra* may be a good species for establishing a canopy quickly in the challenging environmental conditions of a recently restored wetland. Overall, canopy closure in recently restored wetlands may take >6 years and can be facilitated by planting early successional species. Using a larger stocktype may decrease the time to canopy closure by increasing the initial height and canopy diameter.

Beaver Damage

Beavers are a common cause of damage and mortality to saplings and trees in forested wetlands adjacent to streams. At Phase III of the Field study all species had some damage caused by beavers and 6 trees were completely killed as a result of beaver herbivory. The beavers damaged trees with larger diameter stems and *S. nigra* had more damage than other species. These findings suggest that beavers prefer larger saplings and have some species-specific preferences. The occurrence of beavers near restored or created forested wetlands and the potential damage they can cause should be taken into account when determining the amount of trees to plant.

Economic Analysis

In conjunction with selecting planting stock to maximize ecological benefits, minimizing monetary cost is an important consideration when performing wetland restoration/creation. The results of the economic analysis suggest that the bare root stocktype continues to be the least expensive choice to guarantee adequate stem density even though the mortality is higher than the other stocktypes. This result is due to the lower cost associated with purchasing and planting each tree which allows for greater initial planting density to overcome poor survival. Across the entire study for all species the initial planting density needed to reach 400 stems/acre after 6 years is 2500, 1000 and 1300 stems/acre for the bare-root, gallon and tubeling stocktype respectively. These planting densities correspond to ~$4700/acre for bare-root stocktype, ~$10,000/acre for the gallon and ~$5400/acre for the tubeling stocktype.

Species/Stocktype Ranking

In order to determine which species, stocktypes, and combinations have the greatest ecological performance and lowest cost associated with planting, two methods of ranking were used. These two methods yielded similar results for species and successional groups where the primary species had higher rankings than the secondary species (Table 9). However, using only data from year six, the bare-root and gallon stocktypes had similar overall rankings. This suggests that the bare-root stocktype is cheaper and has similar ecological performance to the gallon stocktype after six years. The tubeling stocktype continues to have lesser rankings than the other stocktypes. This change in performance through time will be investigated further.

Biomass Estimation Models

The second objective of this study was to determine the appropriate vegetative measures that will identify whether wetland functions are returning. The results from this study suggest that the basal diameter morphological measurements have a strongly predictive relationship with above and belowground biomass. The morphological measurements of the remaining trees will be used to estimate biomass which will be used to determine woody production and carbon sequestration. These calculated variables will be used to determine which species/stocktypes have greater ecological functioning.

Conclusion

Overall, when choosing the plant material for forested wetland restoration, many factors need to be taken into consideration including, site conditions, budget and species/stocktype selection. The analysis thus far suggests that the primary successional species have greater ecological performance than the secondary successional species. However, in order to enhance biodiversity and diversity of ecological structure and functioning, planting multiple species is preferred. Additionally, the greater planting cost of gallon stocktype may not yield greater ecological performance in the long run compared to planting increased density of bare-root seedlings. (Also see Appendix 5 below.)

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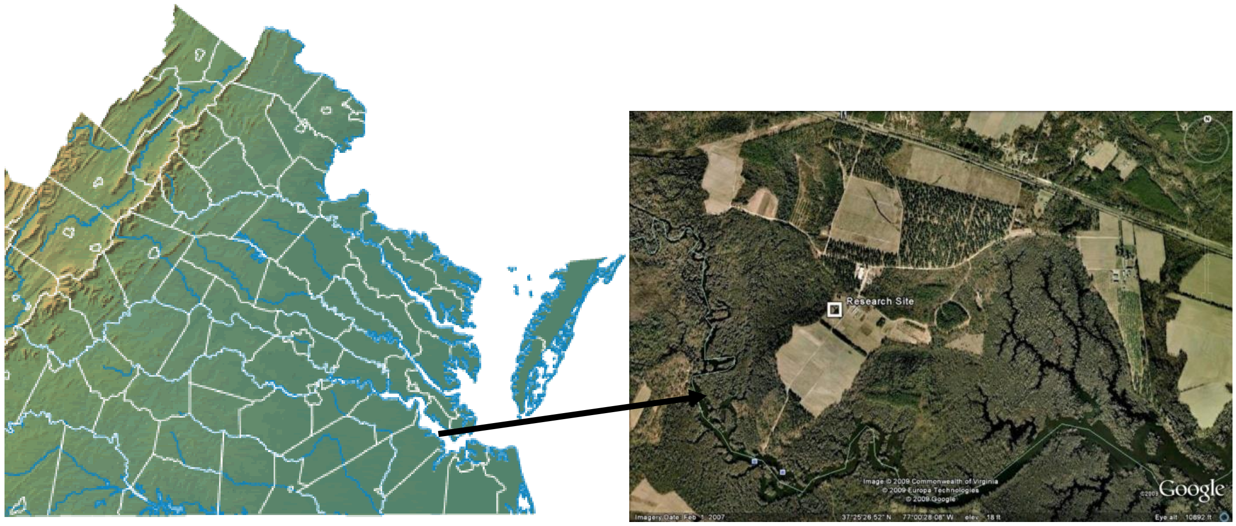
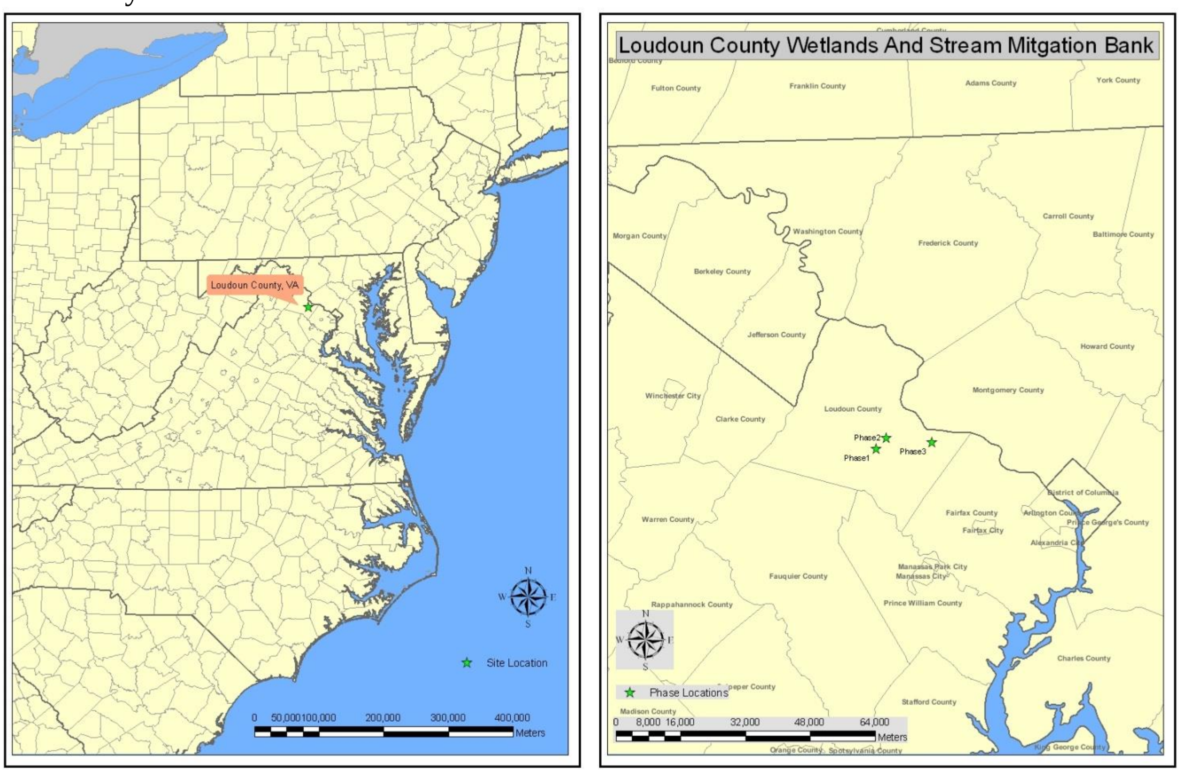
Appendix 1. Location of Mesocosm and Field Studies

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 sheepsfoot 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. List of presentations, posters and student reports

VIMS Student and Faculty Presentations and Posters

Invited Presentations

Hudson III, H. W. and J. E. Perry. 2014. Improving Forested Wetland Restoration: Survival and Growth of 2,772 Trees Over Five Years. Virginia Association of Wetland Professionals. Annual Meeting. May 16, 2014. Richmond, VA.

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 (Ambient, 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 Ambient 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 Ambient, 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 (Ambient, 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 Ambient Cells were similar. Soil carbon and C:N ratios increased from the flooded Cell to the saturated Cell and are highest in the Ambient 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 (Ambient (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 (Ambient, 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 Ambient 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 Ambient 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. 2014. Survival and growth of seven tree species from three stocktypes planted in created wetlands in Loudoun County, Virginia. Society for Ecological Restoration Mid-Atlantic Chapter Annual Meeting. Philadelphia, PA. March 20-22, 2014.

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 (Ambient, 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. Ambient 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 Ambient 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 Publications, Presentations, Posters and Theses

Roquemore, J. D., Hudson III, H. W., Atkinson, R. B., & Perry, J. E. 2014. Survival and growth of seven tree species from three stocktype planted in created wetlands in Loudoun County, Virginia. Ecological Engineering. 64:408-414.

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.)

Appendix 5. Draft Publication
Title: Experimental forested wetland planted tree survival and morphology

Target Journal: Restoration Ecology

Authors: Herman W. Hudson III and James E. Perry

Abstract
The destruction or conversion of forested wetland ecosystems leads to the loss of important ecosystem structures, functions and services from the landscape and this realization has led to the restoration of forested wetlands. One of the major challenges associated with forested wetland restoration has been establishment and growth of trees that return lost structure and ecological functions to the landscape including habitat for plants, animals, fungi, and microbial communities both within the restored wetland and in adjacent and downstream ecosystems. The purpose of this study was to investigate the differences in survival and development of morphological structure (stem diameter, crown diameter, and height) of planted trees in response to; 1) stocktype selection 2) species and 3) soil physical, chemical and hydrologic conditions. Seven native wetland trees common to the mid-Atlantic region of the United States were planted using three stocktypes (bare roots (BR), tubelings (TB), and 1-gallon containers (GAL)) in a large scale, hydrologically controlled, field experiment. The species used in this study were divided into two groups based on dominance during the traditional forest successional sequence, differences in maturation and growth rates, dispersal mechanisms, and disturbance tolerance. The primary (pioneer) species (*Betula nigra* L. (river birch), *Liquidambar styraciflua* L. (sweetgum), *Platanus occidentalis* L. (American sycamore), and *Salix nigra* Marshall (black willow)) and the secondary (late successional) species (*Quercus bicolor* Willd. (swamp white oak), *Quercus palustris* Münchh. (pin oak), and *Quercus. phellos* L. (willow oak)). The experimental site consisted of three hydrologically distinct cells that were manipulated to include an ambient treatment (AMB - received only precipitation), saturated treatment (SAT - kept saturated for a minimum of 90% of the growing season within the root-zone (10 cm) of the plantings and irrigated as needed), and a flooded treatment (FLD - inundated above the root crown for a minimum of 90% of each year). In addition to hydrologic manipulations, there were differences in soil physical and chemical differences among the cells. The FLD cell had increased amounts of clay, higher bulk density and decreased nitrogen and phosphorus concentrations compared to the AMB and SAT. Survival and morphology (height, stem cross-sectional area at groundline, crown diameter) of all trees were measured three times per year (mid-April, mid-August, and mid-October) for 5 years. Differences in survival and morphology among stocktype, species and successional groups were investigated using Cox proportional hazards model and repeated measures analysis of variance respectively. In the FLD cell, the larger stocktype (GAL) exhibited greater survival, stem area and crown diameter compared to the smaller stocktypes (BR and TB) for most species. In the less stressful AMB and SAT cells, the GAL had morphology similar to the BR and TB for most species. Also in the FLD the primary successional species (especially *S. nigra*) exhibited greater survival than secondary successional species, while in less stressed conditions (AMB and SAT) the survival of the secondary species equaled or exceeded the survival of the primary species. The morphology of the primary species was in general greater than that of the secondary successional species. In general trees grown in the AMB had greater survival and were structurally larger than those in FLD and were greater than or equal in size to those grown in the SAT. Trees planted in the SAT cell generally had greater survival and increased size compared to those grown in the FLD. These results suggest that planting primary successional species with larger containerized stocktypes may enhance the return of woody ecosystem structure and ecological functions in the stressful environmental conditions of recently restored forested wetlands. In less stressful environmental conditions, the bare root stocktype grew similarly to the gallon stocktype suggesting that the less expensive bare root stocktype could be used successfully in similar conditions. These results could be used for a variety of tree planting situations besides forested wetland restoration including afforestation, reforestation, carbon sequestration, wildlife habitat creation and other conservation projects.

Introduction

Palustrine forested wetlands, the most abundant wetland type in Virginia, make up a majority of wetland losses in Virginia over the past few decades (Tiner and Finn 1986; USGS 1999; Tiner et al. 2005). The destruction or conversion of wetland ecosystems leads to the loss of important ecological functions and services from the landscape, including but not limited to carbon sequestration, water quality enhancement and protection, water storage, accumulation of sediments, maintenance of characteristic plant communities and provision of animal habitat (NRC 1995). Wetlands located near streams, estuaries or rivers are particularly important for protecting the health and functioning of these nearby ecosystems and ecosystems farther downstream.

Realization of these lost functions and services has led to the restoration of wetlands for a variety of reasons, including compensation for Clean Water Act Section 404 permitted impacts to existing wetlands (wetland compensatory mitigation), re-establishing bird habitat (Ducks Unlimited), agricultural easements (wetland reserve program (WRP), and conservation reserve program (CRP)). Regardless of the underlying reason, many attempts at forested wetland restoration have not been ecologically successful (i.e. ecosystem structures, functions and services have not been restored). One of the major challenges associated with forested wetland restoration has been establishment and growth of trees that provide and enhance habitat for plants, animals, fungi, and microbial communities both within the restored wetland and in adjacent and downstream ecosystems.

Trees provide habitat for many types of organisms within the wetland they are found. Living and shed bark, wood, roots, flowers, fruits, seeds, leaves and sap are consumed by a number of different organisms including, insects, mammals and birds. Leaf litter and fallen dead wood also provide nutrients for fungus and other microorganisms in the detrital food web. Trees provide shelter from weather and predators in the form tree cavities, leaf litter and fallen dead wood. Shade provided by trees can also reduce air and water temperature enhancing habitat for aquatic organisms. Trees also provide space for organisms to live including insects living under and in the bark, birds and mammals building nests in cavities and branches, caterpillars and other insects building nests in the crown and lichen, moss and fungi living on the bark.

Trees living in wetlands enhance the quality of water flowing into downstream ecosystems by trapping sediment by slowing the flow of surface and ground water with stems and roots and stabilizing soil (Dosskey et al. 2010). Additionally, trees remove nutrients from groundwater and assimilate them into biomass which leads to long term retention of nutrients in woody tissue and short term storage in leaves. Trees can also facilitate transformation of nutrients, specifically denitrification which removes nitrogen from ground water, by providing heterogeneous environments around roots and energy (root exudates) for denitrifying microorganisms (Groffman et al. 1996). This process usually takes place where oxygen concentrations are reduced, such as in wetland soils (Mitsch and Gosselink 2007).

Allochthonous organic matter (OM) from trees provide nutrients and shelter for organisms downstream. Forested headwater wetlands in particular can provide a substantial proportion of the total OM found within streams (Dosskey and Bertsch 1994) and can contribute significantly higher concentrations of organic carbon when compared to upland watersheds (Mulholland and Kuenzler 1979). Large woody debris increases channel bed roughness, which can slow stream velocity, increase stability and provide habitat for microbial organisms and animals (Harmon et al. 1986).

All species used in this study (*Betula nigra* L. (river birch), *Liquidambar styraciflua* L. (sweetgum), *Platanus occidentalis* L. (American sycamore), *Quercus bicolor* Willd. (swamp white oak), *Quercus palustris* Münchh. (pin oak), *Quercus. phellos* L. (willow oak) and *Salix nigra* Marshall (black willow)) are known to provide habitat for a variety of organisms.

Betula nigra seeds are consumed by a number of birds (*Bonasa umbellus* (ruffed grouse) and *Meleagris gallopavo* (wild turkey)), leaves and twigs are consumed by *Odocoileus virginianus* (white-tailed deer) and host the fungus *Gloeosporium betularum* (Anthracnose leaf blight), and *Phoradendron serotinum* (Christmas mistletoe) colonizes branches (Burns and Honkala 1990; Sullivan 1993; Van Dersal 1938; Horst 2001). European hornets (*Vespa crabro*) were observed removing bark and consuming sap in this study consistent with findings from Santamour and Greene (1986). The damage also attracted a variety of other insects (hornets, bees, flies and beetles). Witch-Hazel bud gall aphid (*Hamamelistes spinosus*) over winter on river birch and feed on young leaves and bronze birch borer (*Agrilus anxius*) feed on vascular tissue and many caterpillars (including tent caterpillars) feed on and reproduce in branches and foliage (Johnson and Lyon 1988; Adkins et al. 2012). Immature larvae of the birch leafminer (*Fenusa pusilla*) feed between the leaf surface (Latimer and Close 2014). *Acrobasis betulivorella* (species of snout moths) larvae feed on immature terminal leaves of *B. nigra* (Johnson and Lyon 1988).

Liquidambar styraciflua seeds are eaten by birds (*Colinus virginianus* (northern bobwhite), *M. gallopavo* (wild turkey) and several quail), *Sciurus carolinensis* (eastern gray squirrel), and *Tamias striatus* (eastern chipmunk) (Martin et al. 1951; Burns and Honkala 1990; Coladonato 1992; Van Dersal 1938). The small branches and buds are consumed by *O. virginianus* (white-tailed deer) (Harlow et al. 1975; Coladonato 1992) and the bark and cambium are eaten by *Castor canadensis* (North American Beaver) (Martin et al. 1951; Silberhorn 1992). Dead sweetgum trunks (snags) are used by a variety of birds as nesting, perching and foraging areas (Dikson et al 1983). Many fungi, bacteria, and other parasites use *L. styraciflua* as a host and many insects and beetles feed on and live in leaves and bark of living and decaying trees (Johnson and Lyon 1988; Burns and Honkala 1990). Additionally *Meloidogyne* sp. (nematode) feed on the roots (Horst 2001). The treehopper (*Stictocephala militaris*) lives on sweetgum for its entire life cycle (Ebel and Kormanik 1966).

Seeds of *P. occidentalis* are eaten by *Haemorhous purpureus*, (purple finch), and *Spinus tristis* (American goldfinch), *Pecille* spp. (chickadees), *Junco hyemalis* (dark-eyed junco), *Anas platyrhynchos* (mallard), *Ondatra zibethicus* (muskrat), *Castro canadensis* (North American Beaver) and *Sciurus carolinensis* (eastern gray squirrel) (Van Dersal 1938; Martin et al. 1951; Sullivan 1994). *P. occidentalis* is of low value as food for *O. virginianus* (white-tailed deer) and *Meleagris gallopavo* (wild turkey) (Sullivan 1994; Allen and Kennedy 1989). *P. occidentalis* often develop hollow trunks as they grow which can provide shelter for waterfowl and the largest cavities can be used by *Ursus americanus* (American black bear) (Allen and Kennedy 1989; Sullivan 1994). Cavities can also be used by *Strix varia* (Barred owl), *Megascops asio* (Eastern screech-owl), *Myiarchus crinitius* (great crested flycatcher) (Hardin and Evans 1977; Allen 1987; Sullivan 1994). *Aix spnsa* (wood duck) uses *P. occidentalis* for nesting (Dugger and Fredrickson 1992). A large number of fungus and other pathogens live and feed on *Platanus* spp. (Horst 2001).

S. nigra provides habitat to a wide array of organisms. *Sphyrapicus varius* (yellow-bellied sapsucker) pecks holes in bark to feed on the sap (Burns and Honkala 1990; Tesky 1992). The fungus *Pollaccia saliciperda* lives exclusively on members of the Salicaceae family including *S. nigra* (Burns and Honkala 1990; Row and Geyer 2010). Mistletoes (*Phoradendron* spp.) colonize *S. nigra* branches (Burns and Honkala 1990). *O. virginianus* (white-tailed deer), *Cercus canadensis* (elk), *Castro canadensis* (North American Beaver) and other rabbits and rodents eat the twigs, leaves and buds (Van Dersal 1938; Martin et al. 1951; Tesky 1992; Row and Geyer 2010). They flower early in spring and are one of the first plants to provide nectar for bees and other insects (Row and Geyer 2010). The larvae of *Limenitis archippus* (Viceroy) and *Limenitis arthemis* (Red-spotted purple) among others live on *S. nigra* (Row and Geyer 2010). Numerous caterpillars, moths, sawflys, nematodes, beetles, weevils and borers feed and live on *S. nigra* (Johnson and Lyon 1988; Burns and Honkala 1990; Horst 2001; Row and Geyer 2010).

Acorns of *Q. bicolor* are eaten by squirrels, mice, *O. virginianus* (white-tailed deer), *Castro canadensis* (North American Beaver), and *Ursus americanus* (American black bear), other rodents and a variety of birds (Nixon et al. 1970; Burns and Honkala 1990; Snyder 1992; Nesom 2009). Acorns of *Q. phellos* are eaten by ducks, *Meleagris gallopavo* (wild turkey), *Glaucomys Volans* (southern flying squirrel) and other squirrels, *O. virginianus* (white-tailed deer), *Urocyon cinereoargenteus* (gray fox), *Meleagris gallopavo* (wild turkey), *Quiscalus quiscala* (common grackle), *Colaptes auratus* (northern flicker), mice (*Peromyscus* spp.), *Cyanocitta cristata* (blue jay), and *Melanerpes erythrocephalus* (red-headed woodpecker) (Van Dersal 1938; Cypert and Webster 1948; Burns and Honkala 1990; Carey 1992; Moore 2002). Acorns of *Q. palustris* (pin oak) are consumed by woodpeckers, *Anas platyrhynchos* (mallard), *Aix spnsa* (wood duck), *O. virginianus* (white-tailed deer), squirrels, *Meleagris gallopavo* (wild turkey), *Cyanocitta cristata* (blue jay) and other waterfowl (Burns and Honkala 1990; Carey 1992a; Dickerson 2002). These three oaks host a large number of caterpillars, moths, sawflys, acorn weevils, beetles, leafminers, leafrollers, wood borers, gall-wasps, scale insects, aphids, nematodes, midges, sap-suckers, mites, fungi, bacteria and viruses (Johnson and Lyon 1988; Burns and Honkala 1990; Chong et al. 2012).

In the Mid-Atlantic, the abundance of many bird species is positively correlated with tree basal area (Robbins et al. 1989). Neonate whitetail deer in South Dakota were found in areas that have large diameter tree stems and crowns directly following birth (Grovenburg et al. 2010) and in Arkansas, radio tagged adult whitetail deer were more often located in stands with larger basal area than surrounding unused areas (Wigley and Garner 1988). The average diameter at breast height (DBH) of trees used as dens by black bears in southwest Virginia was 85 cm for chestnut and 95 cm for red oaks (Godfrey 1996). Taller trees and forests that have trees of different heights (stratified) provide habitat for a higher diversity of birds (MacArthur and MacArthur 1961). Trees that survive, grow and reproduce in restored wetlands provide habitat for a wide variety of organisms.

Many studies have investigated how different stocktypes survive and grow following outplanting (Burdett et al. 1984; McLeod 2000a; South et al. 2005; Pinto et al. 2011a; Roquemore et al. 2014); however, few studies have investigated how species and stocktype selection influence growth and survival in restored forested wetlands. Denton (1990) investigated the effect of stocktype on the growth of *Taxodium distichum* in a restored forested compensatory mitigation site in Florida. The results suggest that in order to obtain 33% canopy closure the initial costs could be reduced by planting smaller trees (1 gallon container) at ~2500 stems per ha (~1000 stems per acre) as opposed to planting 7 gallon trees at ~1000 stems per ha (~400 stems per acre). Due to the complexities of the species and stocktypes available and lack of information regarding the influence of species and stocktype on the survival of woody species under various hydrologic conditions, managers have encountered difficulties in restoring forested wetlands that will contain the desired ecological structures and woody habitat functions.

The purpose of this study was to investigate the differences in survival and development of morphological structure (stem diameter, crown diameter, and height) of planted trees in response to; 1) stocktype selection 2) species and 3) soil physical, chemical and hydrologic conditions. Seven native wetland trees common to the mid-Atlantic region of the United States were planted using three stocktypes (bare roots, tubelings, and 1-gallon containers) in a large scale, hydrologically controlled, field experiment. This research will assist wetland managers in selecting appropriate species and stocktypes for site conditions in order to increase the probability of successful forested wetland restoration as well as providing data on the development of habitat provided by trees.

Methods

Study Site

The experimental site (here to referred to as “the site”) was established at the New Kent Forestry Center in New Kent County, Virginia, USA in 2008-2009. The forestry center is located in the Coastal Plain Region of Virginia and average yearly temperature is 15^{o} C and the average yearly precipitation is 116.2 cm (39 year average; WEST POINT 2 NW, Coop ID: 449025). The 2.1 ha experimental site is located 8.8 m (29 ft) above sea level and ~1 km (0.62 mile) north of the Chickahominy River (37.423862, -77.014823) (Figure XXX). The site is located on a terrace adjacent to a mature palustrine forested wetland to the west and north with managed upland fields to the east and south. Soil series on the site include Catpoint fine sand, State very fine sandy loam and Altavista fine sandy loam (USDA NRCS 2015). These are classified as somewhat excessively drained, well drained, and moderately well drained respectively. Based on observations at the site, the depth to the natural water table is estimated to be >1 m (>3.3 ft).

The site consisted of three hydrologically distinct cells (ambient (AMB), saturated (SAT) and flooded (FLD)) each 49 m x 144 m (161 ft x 472 ft) in size. Each cell was equipped with an on-site irrigation system capable of producing a minimum of 2.54 cm (1 in.) of irrigation per hour. The three cells were hydrologically manipulated to include an ambient treatment (AMB - received only precipitation), saturated treatment (SAT - kept saturated for a minimum of 90% of the growing season within the root-zone (10 cm) of the plantings and irrigated as needed), and a flooded treatment (FLD - inundated above the root crown for a minimum of 90% of each year). Irrigation water was drawn from the non-tidal portion of the Chickahominy River approximately 8 km (5 mi.) upriver above the Walkers Dam,Walkers, VA. In addition to the hydrologic differences among the cells, there were differences in soil physical and chemical characteristics (Table 1). Soils in the AMB and SAT treatments were tilled using a finger plow to a depth of 20 cm (8 in) in February 2009 prior to planting while the FLD treatment was excavated using a 5 ton backhoe to a depth of 1 m (3.1ft.) to an existing clay layer.

Nursery production techniques are manifold and have led to the use of different stocktypes by the consumer (e.g. bare root seedlings of various ages, tubelings or plugs, containerized, balled and burlapped, live stakes, etc.). These descriptive names can be used to describe the age, size, and production techniques used, which are not uniform throughout the nursery industry. In general bare root seedlings range in age from one to three years old and are typically planted during dormancy without soil surrounding the roots. Tubelings are typically similar in age to bare root seedlings; however, they are planted with tube soil surrounding the roots and are grown in various shaped (square, round) small containers. Seedlings are also grown in larger containers ranging from 1 gallon to >25 gallons. These containerized seedlings are grown to various ages and sizes and are often planted with the soil intact around the root system, which allows for planting later in the season. In general, bare root seedlings are less expensive and are cheaper to plant, while containerized seedlings are more expensive and require more labor and expense to plant.

Three stocktypes of each species were used: bare-root (BR), tubeling (TB), and 1-gallon containers (GAL) (tubelings of *P. occidentalis*, *Q. phellos*, and *S. nigra* had their soil removed by the nursery prior to shipment). In Spring 2009, all combinations of species and stocktypes were planted randomly along rows within each cell. A total of 2,772 trees were planted; ~44 of each species/stocktype combination, for a total of 924 trees per cell. Trees were spaced 2.3 m (7.5 ft) from trees within the row and 2.6 m (8.39 ft) from trees in adjacent rows resulting in a density of 1711 stems/ha (692 stems/acre). Seedlings were purchased from five nurseries; three in Virginia, one in North Carolina, and one in South Carolina. No fertilizers were applied prior to or following planting. Herbaceous competition was controlled around plantings in the AMB and SAT through bimonthly grass cutting and application of glyphosate at the beginning and middle of growing season using commercial backpack sprayers.

Survival and Morphometric Measurements

Providing habitat for other organisms requires that trees planted in restored wetlands must survive transplanting and grow. Structural measurements of sapling morphology used in this study (crown and stem diameter and height) and survival rates are used to provide inferences about of the amount of habitat provided by individual and stands of trees since specific amounts of habitat resources provided by trees are difficult to quantify (Cade 1987), they are commonly measured in forest inventories, and they have direct and indirect relationships to the occurrence and abundance of other organisms.

Survival counts and morphometric measurements were made in mid-April, mid-August, and mid-October from 2009 to 2013. Individual survival was based on the presence of green leaves during the growing season. If green leaves were lacking, tree survival was finally determined by the presence of live cambium obtained via small scratches beginning at the highest point on the stem, then at the vertical midpoint, and finally at the base. Percent survival calculations excluded live trees removed for biomass measurements.

Morphology measurements included height of tallest stem (H), stem cross-sectional diameter at groundline (used to calculate stem cross-sectional area at groundline (CSAG)), and crown diameter (CD). Data were collected using methods modified from Bailey et al. (2007). Total heights were measured with a standard meter stick, 5-m stadia rod or clinometer, while crown diameter was quantified using macro-calipers (Haglof, Inc. "Mantax Precision" Calipers) or tape measure. Micro-calipers (SPI 6"/0.1 mm Poly Dial Calipers) were used to measure the diameter of all stems at ground level. A single CSAG was calculated for trees having multiple stems originating from below ground by summing CSAG for each stem of an individual. Three measurements of crown diameter were used to determine the average crown diameter.

Species Grouping

To facilitate analysis and interpretation of species selection, species were divided into two groups based on dominance during the traditional forest successional sequence, differences in maturation and growth rates, dispersal mechanisms, and disturbance tolerance. Referred to as primary species and secondary species, the primary species consisted of 4 woody species (*B. nigra*, *L. styraciflua*, *P. occidentalis* and *S. nigra*) that are typically dominant during the early stages of succession, have rapid growth and maturation rates, have wind dispersed seeds and are moderately tolerant of disturbance. The secondary species group consisted of 3 species (*Q. bicolor*, *Q. palustris,* and *Q. phellos*) typically dominant in the later stages of succession, have slower growth and maturation rates, have large seeds that are dispersed mainly by animals and are generally less tolerant of disturbance.

Statistical Analysis

To determine the differences in survival over five years among stocktypes, species and successional groups, Cox proportional hazards model was applied to each species or stocktype within each cell (Firth correction and Breslow method for ties). To determine the differences in morphological variables over five years among stocktype, species, and successional groups, repeated measures analysis of variance (rANOVA) was used within each cell (Covariance structure: Autoregressive 1, Estimation method: Residual maximum likelihood). If significant interactions were found for either survival or morphological variables, a simple effects model was used to determine differences among the stocktypes or successional group for each species within each cell. Least squares post hoc test using a Bonferonni adjustment was used to determine differences among each stocktype. All alpha values were set at 0.05.

Due to the cells unreplicated design the survival and morphology of the 21 unique combinations of species and stocktypes were compared among the cells. Survival was not compared statistically but compared using only percent survival among species/stocktype combinations. To determine differences in morphological variables after 5 years among the cells (representing different soil physical, chemical and hydrologic conditions), a one-way analysis of variance (ANOVA) was used. Least squares post hoc test using a Bonferonni adjustment was used to determine differences among each cell.

Results from each post hoc comparison (stocktype, successional group, cells) for each measured variable (survival, CSAG, H, and CD) were tallied by unique outcome. For example, when comparing the survival among the stocktypes the number of times a particular outcome occurred (BR>GAL, BR=GAL, BR<GAL, TB<GAL, TB=GAL, TB>GAL, BR=TB, or BR<TB) was counted for each cell. The total number of times each outcome occurred across all measured variables was obtained for each cell and in total, to determine which outcome was most common. This analysis also allowed for survival and morphology results to be combined and will be presented as such.

Results

Stocktype Comparison

There were significant interactions between species and stocktype within the Ambient cell (AMB), Saturated cell (SAT), and Flooded cell (FLD) for each parameter (survival, stem cross-sectional area at groundline (CSAG), height (H) and crown diameter (CD)) (Table 2). This suggests that within each cell, response of stocktype depended upon species and vice versa (e.g. GAL stocktype may not have greatest survival or H across all species). As a result of significant interactions, subsequent analysis focused on determining differences among stocktype in each cell for each species separately.

Survival

After five years average percent survival across all cells, species and stocktypes was 57%. Average percent survival for bare root (BR), gallon (GAL), and tubeling (TB) stocktype (across all cells and species) respectively was 48%, 81%, and 43%, respectively. In order to further investigate differences among stocktypes, survival of stocktypes by species were compared within each cell.

In the AMB, GAL survival was greater than BR survival for *B. nigra*, *L. styraciflua*, *P. occidentalis*, *Q. palustris*, *Q. phellos*, and *S. nigra*. Similarly, GAL survival was greater than TB survival for *B. nigra*, *L. styraciflua Q. bicolor*, *Q. palustris*, *Q. phellos*, and *S. nigra*. BR survival was greater than TB survival for *L. styraciflua*, *Q. bicolor* while *Q. palustris* had greater survival in BR than TB (Figure S1 and Table S1). Overall, BR survival was similar to TB for *B. nigra* and *Q. phellos*.

In the SAT, GAL survival was greater than BR survival for *B. nigra*, *L. styraciflua*, *P. occidentalis*, *Q. phellos*, and *S. nigra* and had greater survival than TB for all seven species. BR survival was not different than TB survival for *B. nigra*, *P. occidentalis*, *Q. phellos*, and *S. nigra*. However, BR survival was greater than TB survival for *L. styraciflua Q. bicolor* and *Q. palustris* (Figure S1 and Table S1).

In the FLD, GAL survival was greater than BR survival for *B. nigra*, *L. styraciflua*, *P. occidentalis*, *Q. bicolor*, *Q. palustris*, and *Q. phellos*. GAL survival was greater than TB survival for *L. styraciflua*, *P. occidentalis*, *Q. bicolor*, *Q. palustris*, and *Q. phellos*. There was no difference in survival between BR and TB for *L. styraciflua*, *P. occidentalis*, and *Q. palustris*. *S. nigra* had no differences in survival among all stocktypes in FLD (Figure S1 and Table S1).

Morphology

<u>Stem Cross-sectional Area at Groundline</u>

Average stem cross-sectional area at groundline (CSAG) and standard deviation (SD) for BR, GAL, and TB stocktype (across all cells and species) was 59.6 cm^2 (n=440, SD=114.6 cm^2), 79.8 cm^2 (n=678, SD=137.4 cm^2), and 75.8 cm^2 (n=346, SD=135.9 cm^2), respectively after five years. In order to further investigate differences among stocktypes, CSAG of stocktypes by species were compared within each cell.

In the AMB, GAL CSAG was greater than BR CSAG for *B. nigra*, *Q. phellos* and *S. nigra*. There was no difference in CSAG between BR and GAL stocktypes for *L. styraciflua*, *P. occidentalis*, *Q. bicolor*, or *Q. palustris*. GAL CSAG was greater than TB CSAG for *B. nigra*, *L. styraciflua*, *Q. bicolor*, *Q. palustris* and *Q. phellos*. There was no difference in CSAG between TB and BR stocktype for *B. nigra*, *P. occidentalis*, *Q. palustris*, *Q. phellos*, or *S. nigra* (Figure S2 and Table S3).

In the SAT, GAL CSAG was greater than BR CSAG for *B. nigra*, *Q. palustris*, and *Q. phellos*. There was no difference in CSAG between BR and GAL stocktypes for *L. styraciflua*, *P. occidentalis*, *Q. bicolor* and *S. nigra*. GAL CSAG was greater than TB CSAG for *B. nigra*, *L. styraciflua*, *Q. bicolor*, *Q. palustris* and *Q. phellos*. There was no difference in CSAG between BR and TB for *B. nigra*, *L. styraciflua*, *P. occidentalis*, *Q. palustris*, *Q. phellos*, and *S. nigra* (Figure S2 and Table S3).

In the FLD, GAL CSAG was greater than BR CSAG for *B. nigra*, *L. styraciflua*, *P. occidentalis*, *Q. palustris*, *Q. phellos*, and *S. nigra*. GAL CSAG was greater than TB CSAG for all seven species. BR CSAG was greater than TB CSAG for *Q. bicolor* only (Figure S2 and Table S3).

<u>Crown Diameter</u>

BR, GAL, and TB average crown diameter (CD) after five years was 209.3 cm (n=440, SD=158.9 cm), 241.2 cm (n=678, SD=172.6), and 220.2 cm (n=346, SD= 189.9 cm) respectively (across all cells and species). In order to further investigate differences among stocktypes, CD of stocktypes by species were compared within each cell.

In the AMB, GAL CD was greater than BR CD for *B. nigra*, *Q. palustris*, *Q. phellos*, and *S. nigra*. There was no difference between BR and GAL CD for *L. styraciflua*, *P. occidentalis*, and *Q. bicolor*. GAL CD was greater than TB CD for all seven species except *P. occidentalis* (no difference). BR CD was not different than TB CD for *B. nigra*, *P. occidentalis*, *Q. bicolor*, *Q. phellos* and *S. nigra*. BR CD was greater than TB CD for *L. styraciflua* and *Q. palustris* (Figure S3 and Table S5).

In the SAT GAL CD was greater than BR CD for *B. nigra*, *Q. palustris*, *Q. phellos*, and *S. nigra*. There was no difference between BR and GAL CD for *L. styraciflua*, *P. occidentalis*, and *Q. bicolor*. GAL CD was greater than TB CD for *L. styraciflua*, *Q. bicolor*, *Q. palustris*, *Q. phellos*, and *S. nigra*. There was no difference in CD between TB and GAL stocktype for *B. nigra* and *P. occidentalis*. There was no difference between BR and TB CD for all species except *Q. bicolor*. (Figure S3 and Table S5).

In the FLD, GAL CD was greater than BR and TB CD for all seven species. BR CD was greater than TB for all seven species except *Q. bicolor* (Figure S3 and Table S5).

<u>Height</u>

After five years, average height (H) for BR, GAL, and TB (across all cells and species) was 314.6 cm (n=440, SD=249.1 cm), 345.6 cm (n=678, SD=241.7 cm), and 337.5 cm (n=346, SD=303.0 cm) respectively. In order to further investigate differences among stocktypes, H of stocktypes by species were compared within each cell.

In the AMB, GAL H was greater than BR H for *B. nigra*, *Q. palustris*, *Q. phellos*, and *S. nigra*. There was no difference in H between BR and GAL for *L. styraciflua*, *P. occidentalis*, and *Q. bicolor*. GAL H was greater than TB H for *B. nigra*, *L. styraciflua*, *Q. bicolor*, *Q. palustris*, and *Q. phellos*. There was no difference between TB and GAL H for *P. occidentalis* and *S. nigra*. There was no difference in H between BR and TB for *B. nigra*, *P. occidentalis*, *Q. bicolor*, *Q. phellos* and *S. nigra*. BR H was greater than TB H for *L. styraciflua* and *Q. palustris* (Figure S4 and Table S7).

In the SAT, there was no difference in H between BR and GAL for *L. styraciflua*, *P. occidentalis*, *Q. bicolor*, *Q. palustris* and *S. nigra*. GAL H was greater than BR for *B. nigra* and *Q. phellos*. GAL H was greater than TB H for *L. styraciflua*, *Q. bicolor*, *Q. palustris*, and *Q. phellos.* There was no difference between TB H and GAL H for *B. nigra*, *P. occidentalis*, and *S. nigra*. There was no difference in H between BR and TB for *B. nigra*, *P. occidentalis*, *Q. bicolor*, *Q. phellos* and *S. nigra*. BR H was greater than TB H for *L. styraciflua* and *Q. palustris* (Figure S4 and Table S7).

In the FLD, GAL H was greater than BR height for all species except *Q. bicolor*, for which BR H was greater than GAL height. GAL H was greater than TB H for all species. There was no difference in BR H and TB H for *B. nigra*, *P. occidentalis*, *Q. phellos*, and *S. nigra*. BR H was greater than TB H for *L. styraciflua*, *Q. bicolor*, and *Q. palustris* (Figure S4 and Table S7).

Combining survival and morphology

When combining survival and morphological comparisons for each species across all three cells and counting the number of times an outcome occurred, GAL was greater than BR and TB in 67% and 82% of all comparisons respectively and BR was not different than TB in 69% of comparisons (Table 5). To further investigate differences among stocktypes, outcomes were counted within each cell.

For all species in the AMB, GAL was greater than BR and TB in 61% and 79% of all survival and morphological comparisons respectively and BR was not different than TB in 61% of all comparisons. BR was not different than GAL in 39% of all comparisons and BR was greater than TB in 32% of all comparisons (Table 5).

For all species in the SAT, GAL was greater than BR in 50% of combined comparisons and was not different than BR in 50% of all comparisons. GAL was greater than TB in 75% of the comparisons while BR was not different than TB in 75% of all comparisons. BR was greater than TB in 25% of all comparisons (Table 5).

For all species in the FLD, GAL was greater than BR in 89% of all survival and morphological comparisons and was greater than TB in 93% of all comparisons. BR and TB were not different in 71% of all comparisons (Table 5).

Species Group Comparison

The seven species were divided into two groups (primary and secondary) based on dominance during the traditional forest successional sequence, differences in maturation and growth rates, dispersal mechanisms, and disturbance tolerance in order to facilitate comparisons among species. When analyzing differences in survival, CSAG and H among successional groups and stocktype there were significant interactions between successional group and stocktype within AMB and FLD, SAT and FLD, and FLD respectively. This suggests that the survival, CSAG and H response of stocktype depended upon successional group and vice versa. There was no significant interaction among successional group and stocktype when analyzing differences in CD (Table 3). This suggests that CD response was similar among stocktypes for all successional groups and vice versa. As a result of significant interactions, subsequent analysis of each parameter focused on determining differences among successional groups in each cell for each stocktype separately.

Survival

Survival of secondary species (oaks) was greater than survival of primary species when planted as BR in the AMB. When planted as GAL or TUB there was no difference between the survival of the primary and secondary successional species (Figure S5). In the SAT secondary species (oaks) had greater survival than primary species when planted as BR. When planted as GAL or TUB there were no differences between survival of primary and secondary successional species (Figure S5). For all stocktypes primary successional species had greater survival than secondary species in FLD (Figure S5).

Morphology

Primary species had greater CSAG and H than secondary species for all stocktypes across all cells (Figure S6 and S8). Primary species had greater CD than secondary species for all stocktypes in the AMB and SAT. In the FLD primary species had greater CD than secondary species for GAL and TB stocktype. There was no difference in CD between primary and secondary species for BR (Figure S7).

Primary successional species were greater than secondary successional species in 81% of all comparisons when merging survival and morphological comparisons for each stocktype across all three cells (Table 6). In order to investigate these results further, survival and morphology comparisons were combined for each cell and differences between stocktype and successional stages were investigated.

Combining survival and morphology

In the AMB, when combining survival and morphological measurements for each stocktype primary species were greater than secondary species in 75% of comparisons (Table 6). Primary species were greater than secondary species in 100% of combined survival and morphological comparisons in the SAT (Table 6). In the FLD, primary species were greater than secondary species in 66% of all comparisons. There were no differences between primary and secondary species in 25% of comparisons in the FLD (Table 6).

Cell Comparison

Individual species/stocktype combination's responses after five years were compared among cells in order to make inferences about their responses to environment conditions and to infer about differences among cells. Due to unreplicated nature of cells, survival was compared using absolute values, while CSAG, H and CD were compared statistically (Table 4). The majority of species/stocktype combinations had significantly different responses among the cells, except *Q. palustris* and *Q. phellos* TB (Table 4). The results of the individual measurements comparisons are presented below.

Survival

BR survival after five years was greater in AMB than SAT for *P. occidentalis.* BR survival in the SAT was greater than AMB for *B. nigra, L. styraciflua, Q. bicolor, Q. palustris, Q. phellos,* and *S. nigra*. All seven species BR survival was greater in the AMB and SAT compared to the FLD, except for *S. nigra*. *S. nigra* BR had greater survival in the FLD compared to both the SAT and AMB (Table S2).

GAL survival after five years was greater in AMB than SAT for *B. nigra, Q. palustris,* and *S. nigra*. GAL survival in SAT was greater than survival in AMB for *L. styraciflua, P. occidentalis,* and *Q. phellos*. While, *Q. bicolor* GAL had no difference in survival between the AMB and SAT. All seven species GAL survival was greater in the AMB and SAT compared to the FLD, except for *S. nigra*. *S. nigra* GAL had greater survival in the FLD compared to both the SAT and AMB (Table S2).

TB survival after five years was greater in AMB than SAT for *P. occidentalis* and *S. nigra* while the remaining 5 species TB survival was greater in the SAT than AMB. *P. occidentalis, Q. bicolor*, *Q. palustris* and *Q. phellos* TB survival in AMB and SAT was greater than FLD. However, *B. nigra, L. styraciflua,* and *S. nigra* TB survival in the FLD was greater than AMB and SAT (Table S2).

Morphology

Stem Cross-sectional Area at Groundline

The average BR CSAG after five years in the AMB, SAT and FLD was 90.7 cm^2 (n=182, SD=147.0 cm^2), 49.0 cm^2 (n=183, SD=89.3 cm^2), 10.6 cm^2 (n=76, SD=21.3 cm^2) respectively. The average GAL CSAG after five years in the AMB, SAT and FLD was 126.8 cm^2 (n=261, SD=178.2 cm^2), 73.3 cm^2 (n=268, SD=108.9 cm^2), 9.2 cm^2 (n=149, SD=12.1 cm^2) respectively. The average TB CSAG after five years in the AMB, SAT and FLD was 148.5 cm^2 (n=111, SD=196.1 cm^2), 58.3 cm^2 (n=157, SD=84.8 cm^2), 7.4 cm^2 (n=78, SD=15.0 cm^2) respectively. In order to further investigate differences among cells, CSAG of species within cells were compared for each stocktype.

BR CSAG in AMB was greater than SAT after five years for *B. nigra*, *L. styraciflua*, and *Q. palustris.* There was no difference in BR CSAG between the AMB and SAT for *P. occidentalis, Q. bicolor, Q. phellos*, and *S. nigra.* BR CSAG in AMB was greater FLD for *B. nigra*, *L. styraciflua*, and *Q. palustris*. BR CSAG was not different between AMB and FLD for *Q. bicolor, Q. phellos,* and *S. nigra* (Table S4).

GAL CSAG in AMB was greater than SAT for *B. nigra, P. occidentalis, Q. bicolor,* and *Q. palustris*. There was no difference between GAL CSAG in AMB and SAT for *L. styraciflua*, *Q. phellos,* and *S. nigra*. All seven species CSAG for GAL was greater in the AMB compared to FLD.

TB CSAG after five years was greater in AMB than SAT for *B. nigra, P. occidentalis, Q. bicolor*. There was no difference in TB CSAG between AMB and SAT for *L. styraciflua, Q. palustris, Q. phellos,* and *S. nigra*. TB CSAG was greater in the AMB than FLD for *B. nigra, L. styraciflua, Q. bicolor*, and *S. nigra*. There was no difference in TB CSAG between AMB and FLD for *P. occidentalis* and *Q. palustris*. TB CSAG was greater in the SAT than FLD for *B. nigra, L. styraciflua,* and *S. nigra*. There was no difference in TB CSAG between SAT and FLD for *P. occidentalis, Q. bicolor,* and *Q. palustris* after five years.

Crown diameter

The average BR CD after five years in the AMB, SAT and FLD was 277.2 cm (n=182, SD=168.9 cm), 205.5 cm (n=182, SD=131.8 cm), 56.1 cm (n=76, SD=45.0 cm) respectively. The average GAL CD after five years in the AMB, SAT and FLD was 326.8 cm (n=261, SD=175.8 cm), 257.9 cm (n=268, SD=136.2 cm), 61.2 cm (n=149, SD=50.7 cm) respectively. The average TB CD after five years in the AMB, SAT and FLD was 329.7 cm (n=111, SD=214.1 cm), 228.9 cm (n=157, SD=151.4 cm), 46.7 cm (n=78, SD=42.1 cm) respectively. In order to further investigate differences among cells, CD of species within cells were compared for each stocktype.

BR CD after five years was greater in AMB than SAT for *L. styraciflua, P. occidentalis, Q. bicolor,* and *Q. palustris*. There was no difference in BR CD between AMB and SAT for *B. nigra* and *Q. phellos*, while BR *S. nigra* CD was greater in SAT than AMB. All seven species had greater BR CD in the AMB than FLD except *S. nigra* (no difference). All seven species had greater BR CD in the SAT than FLD (Table S6).

GAL CD was greater in AMB than SAT for *B. nigra*, *P. occidentalis, Q. bicolor,* and *Q. palustris*. There was no difference in GAL CD between AMB and SAT for *L. styraciflua, Q. phellos,* and *S. nigra*. All seven species GAL CD in AMB and SAT was greater than FLD (Table S6).

TB CD was greater in the AMB than SAT for Q. *bicolor*, while the remaining six species had no difference in TB CD between AMB and SAT. TB CD was not different between AMB and FLD for *Q. palustris,* while the remaining six species TB CD was greater in the AMB than FLD. TB CD was greater in SAT than FLD for *B. nigra, L. styraciflua,* and *S. nigra*. TB CD was not different between SAT and FLD for *P. occidentalis, Q. bicolor,* and *Q. palustris* (Table S6).

Height

The average BR H after five years in the AMB, SAT and FLD was 435.7 cm (n=182, SD=278.2 cm), 286.7 cm (n=182, SD=188.8 cm), 91.2 cm (n=76, SD=47.7 cm) respectively. The average GAL H after five years in the AMB, SAT and FLD was 485.8 cm (n=261, SD=251.4 cm), 345.8 cm (n=268, SD=179.4 cm), 99.7 cm (n=149, SD=52.3 cm) respectively. The average TB H after five years in the AMB, SAT and FLD was

545.3 cm (n=111, SD=365.1 cm), 318.1 cm (n=157, SD=210.0 cm), 80.8 cm (n=78, SD=41.3 cm) respectively. In order to further investigate differences among cells, H of species within cells were compared for each stocktype.

BR H after five years was not different between AMB and SAT for *S. nigra*, while the remaing six species BR H was greater in the AMB than SAT. All seven BR species H was greater in the AMB than FLD. BR H was greater in the SAT than FLD for *B. nigra*, *L. styraciflua*, *Q. phellos,* and *S. nigra*, while BR H was not different between the SAT and FLD for *Q. bicolor* and *Q. palustris* (Table S8).

After five years GAL H was greater in AMB than FLD or SAT and GAL H was greater in SAT than FLD for all seven species. (Table S8).

TB H was greater in the AMB than SAT for *B. nigra, P. occidentalis, Q. bicolor,* and *S. nigra*. TB H was not different between AMB and SAT for *L. styraciflua, Q. palustris,* and *Q. phellos*. TB H was greater in the AMB than FLD for *B. nigra, L. styrcaiflua, P. occidentalis, Q. bicolor,* and *S. nigra*. There was no difference in H between AMB and FLD for *Q. palustris* TB. TB H was greater in the SAT than FLD for *B. nigra, L. styrcaciflua,* and *S. nigra*. TB H was not different between SAT and FLD for *P. occidentalis, Q. bicolor,* and *Q. palustris* (Table S8).

Combining survival and morphology

To further analyze the differences among cells, the survival and morphology measurements across all species and stocktypes were combined (Table 7). In total, the outcomes of the comparisons of species/stocktype comparisons among cells show that the AMB was greater than the SAT in 50% of comparisons, while there was no difference among the AMB and SAT in 32.1% of comparisons and the SAT exceeded the AMB in 17.9% of comparisons. The AMB exceeded the SAT mainly in percent survival comparisons. When comparing the AMB to FLD, the AMB was greater than the FLD in 83.3% of comparisons and equal to in 10.3%. The SAT exceeded the FLD in 71.8% of comparisons and was similar to the FLD in 21.8% of comparisons. Based on the responses of the species/stocktype combinations, these results suggest that the AMB was more similar to the SAT than the SAT was similar to the FLD, while the AMB and FLD are most dissimilar.

Discussion

The goal of wetland restoration is to return lost ecological structure and functions to the landscape, including plant, animal, and microbial habitat. Habitat in restored wetlands is obtained primary through the successful establishment of vegetative structure which provide cover, food and space for a variety of organisms. Numerous studies have found that tree density and tree growth were significantly lower for restored sites as compared to conditions prior to conversion or nearby mature forested wetlands (Brown and Veneman 2001; NRC 2001; Cole and Shafer 2002; Sharitz et al. 2006; Matthews and Endress 2008). Poor establishment and growth may result from inadequate colonization from surrounding seed sources or low survival of planted woody vegetation (Robb 2002; Morgan and Roberts 2003). Poor survival and growth of planted trees results from unfavorable site conditions (inappropriate hydrology, low organic content, high bulk density, increased rock fragments), competition from non-desired species, improper species or stocktype selection, and/or improper planting techniques (Stolt et al. 2000; Campbell et al. 2002; Bruland and Richardson 2004; Bergshneider 2005; Daniels et al. 2005; Bailey et al. 2007). The effect of stocktype, species and hydrology on planted tree survival and morphology were the focus of this project.

Stocktype Comparison

In the stressful hydrologic, soil and competitive herbaceous conditions of the flooded cell (FLD), the larger stocktype (GAL) exhibited increased survival, crown diameter (Figure 1), and total CSAG compared to smaller stocktypes (BR and TB) for most species. The characteristics of GAL (larger initial size, organic rich potting soil surrounding roots) may have increased its ability to overcome transplant shock, competition from herbaceous vegetation and low soil nutrient concentrations in the FLD treatment.

Transplant shock (also called planting check) is a temporary setback in growth that occurs after outplanting, which if severe enough can result in tree mortality (Kozlowski and Davies 1975; Acquaah 2005;

Grossnickle 2005; South and Zwolinski 1996). Transplant shock is associated with decreased water absorption as a result of poor root-soil contact, low permeability of suberized roots (older woody roots) and a low amount of roots in relation to shoots (Beineke and Perry 1965; Carlson and Miller 1990; South and Zwolinski 1996; Grossnickle 2005). In order to overcome transplant shock, saplings must absorb enough water to satisfy evapotranspiration and metabolic/physiologic processes. The stressors associated with transplant shock in recently restored wetlands may be greater due to the low oxygen soil conditions present.

The larger initial size of GAL suggests that it may have had greater initial above- and below-ground biomass than the BR and TB stocktypes. Increased belowground biomass has been shown to increase the amount of water absorbed by roots (Carlson 1986) and trees with increased initial above-ground biomass have been shown to overcome herbaceous competition (Grossnickle and El-Kassaby 2015). Additionally, the gallon stocktype was planted with organic rich potting soil surrounding the root mass, which may have enhanced the probability for survival and overall growth because the roots would have remained in contact with the potting soil and continued to take up water. Furthermore, the potting soil may have provided additional nutrients not available in the surrounding soil. Overall, the initial characteristics of GAL (larger initial size, organic rich potting soil surrounding roots) may be reasons for the greater survival and overall growth than the BR and/or TB stocktypes in the FLD cell.

Previous research has also demonstrated that large containerized woody stock had better survival and/or growth than smaller planting stocks. Burdett et al. (1984) showed that container grown seedlings can have greater root growth during their first growing season after outplanting compared to bare root seedlings. South et al. (2005) also showed that containerized seedlings of *Pinus palustris* had 20% better survival than bare root seedlings having similar root-collar diameters when outplanted on old-fields and cutover sites. Pinto et al. (2011a) found that larger containers of *Pinus ponderosa* planted at a mesic site had increased total height and basal area. A meta-analysis of 122 trials comparing survival between bare-root and containerized stock planted across a variety of sites found that containerized stock had greater survival than bare-root stock in 60.7% of the trials (Grossnickle and El-Kassaby 2015).

In more aerobic soil conditions (AMB and SAT) the GAL stocktype has similar morphology compared to the BR for most species, but was often larger than the TB stocktype. This suggests that the less expensive BR stocktype may return ecosystem structure and possibly ecosystem habitat functions in a similar manner as a larger stocktype if hydrologic stress and herbaceous vegetation competition is reduced and there are better soil conditions (low bulk density, high soil nutrient concentrations). However, these results suggest that the TB stocktype may not be appropriate for planting into restored wetlands.

Several previous studies have similarly found that bare-root seedlings have similar survival and growth compared to the more expensive containerized stocktype. A large scale long term study by McLeod (2000a) found that bare root seedlings had similar survival to more expensive containerized seedlings of *Fraxinus pennsylvanica*, *Nyssa aquatica*, and *Taxodium distichum* when planted in a thermally impacted bottomland hardwood forest. Additionally, Denton (1990) investigated the effect of stocktype on the growth of *T. distichum* in restored forested wetlands in Florida and their results suggest that in order to obtain 33% canopy closure the initial costs could be reduced by planting smaller trees (1 gallon container) at ~2500 stems per ha (~1000 stems per acre) as opposed to planting 7 gallon trees at ~1000 stems per ha (~400 stems per acre). A large meta-analysis comparing container grown seedlings and bare-root seedlings found that on a variety of sites with low stress, the two stocktypes had similar survival rates (Grossnickle and El-Kassaby 2015). While not focusing on wetlands, these results are similar to the present study.

Recently restored wetlands often have stressful hydrologic conditions (persistent high water tables) and vegetative competition (Cole and Brooks 2000, Campbell et al. 2002, Bruland and Richardson 2004, DeBerry and Perry 2004). The overall results from the present study suggest that using a larger stocktype that has increased survival and grows quickly is returning lost ecological structure and functions more than other smaller stocktypes when planting in recently restored wetlands. However, less expensive stocktype could be utilized in less stressful environmental conditions to obtain similar amounts of ecological structures and functioning.

Species Group Comparison

Survival

In stressed environmental conditions (FLD) the primary successional species (especially *S. nigra*) exhibited greater survival than secondary successional species while in less stressed conditions (AMB and SAT) the survival of the secondary species equaled or exceeded the survival of the primary species.

Primary successional species have adaptations that allow for establishment following planting in harsh environmental conditions while secondary species may lack these adaptations. The physiological and morphological traits that may enhance establishment of primary successional tree species are high photosynthetic and growth rates, high acclimation potential, fast recovery from resource limitation, fast resource acquisition rates and high competitive ability in early successional stages (Bazzaz, 1979; Brzeziecki and Kienast, 1994; Huston and Smith 1987).

Simmons et. al. (2012) found that the survival, growth and vigor of early successional species were greater than later successional species when planted in different microtopographic treatments (ridges, flats, and mound-and-pool) after 2 years in a riparian forest restoration. They suggest that some early successional species may be more appropriate for restoration if they are adapted to disturbed environmental conditions. Our results confirm that secondary species alone may not be appropriate for returning ecological structure or restoring habitat functions in recently created or restored wetlands because of the harsh environmental conditions often found during this time. Therefore, we conclude that primary species will more quickly return more tree stem structure and ecological functions than secondary successional species especially in harsh environmental conditions. For example, *S. nigra*, though short lived, has many adaptations (shallow roots, rapid growth, adventitious rooting etc.) to harsh environmental conditions and appears to be a good species for forested wetland restoration in degraded habitats.

Morphology

The H, CD and CSAG of the primary successional species regardless of stocktype was almost always larger than the secondary successional species due to primary successional species characterization of greater growth rates than secondary species (to be investigated in subsequent publications) (Figure 2). Farmer (1980) compared first-year growth of six deciduous species grown in nursery conditions and found that early successional species (*Liriodendron tulipifera* and *Prunus serotina*) had higher growth rates, net assimilation rates and high investment in leaf area than late successional species (*Q. rubra*, *Q. prinus*, *Q. alba*, and *Q. ilicifolia*). Results from Farmer (1980) and the present study suggest that primary successional species are returning ecological structure that provides the ecosystem habitat function at a faster rate than the secondary successional species across a variety of environmental conditions.

Cell comparison

When survival and morphology measurements were combined across all species/stocktype combinations, in general those trees grown in the AMB had greater survival and were structurally larger than those in FLD and were greater than or equal in size to those grown in the SAT which generally had greater survival and increased size compared to those grown in the FLD. These results suggests that the environmental conditions in the FLD (flooded hydrologic conditions, uncontrolled herbaceous competition, higher clay content, higher bulk density, reduced soil nutrient pools) caused stress to the trees planted there in excess of their physiological tolerances. This also suggests that the initial soil, hydrologic and competitive conditions present during restoration can affect the development of ecological structure and functions provided by trees.

Reduction in tree survival and growth can be attributed to prolonged saturated or flooded soil conditions which remove the plant available oxygen from the soil pore space. The reduction in oxygen leads to a lack of aerobic respiration in roots, which decreases the energy available for trees to maintain functions of existing tissues (Hale and Orcutt 1987; Brady and Weil 2002). Many growth chamber, greenhouse, mesocosm and field experiments have investigated the effect of hydrology on a multitude of responses across many species of trees. While species specific responses may vary (e.g. *Taxodium disticum*, mangroves) most species exhibit decreased survival and growth when grown under prolonged inundation. Niswander and Mitch (1995) planted ten tree species (three of which were used in this study, *B. nigra*, *L. styraciflua*, *Q. palustris)* across a hydrologic gradient in a created wetland. Similar to the results in this study, they found that trees planted in shallow water died or were severely stressed, and that trees planted in the wet meadow portion were able to survive and grow, while trees planted in the upland section were the largest and had the densest foliage. Pennington and Walters (2006) investigated growth and survival four species (two of which were used in this study, *Q. palustris* and *Q. bicolor*) planted in three hydrologic zones (wetland, transition, upland) of created perched wetlands. Again, similar to the present study, trees grown in the transitions zone (high soil water availability with oxidized root zone) had greater height growth and survival after 5 years than those planted in the wetland zone (reduced oxygen in the root zone). Bailey et al. (2007) investigated the effect of organic matter loading rates and elevation in a created wetland on several vegetation responses including the growth of planted *B. nigra*. Results suggested that the early growth of planted trees responded to both OM loading rates and hydrology related to elevation. In the lower elevations (higher water table) the tree growth rates were reduced compared to those in the higher elevations, consistent with results of *B. nigra* from the present study. From the present study and previous studies, stressful hydrologic conditions reduce the ecological structure and functions associated with planted trees.

The spatial location of herbaceous vegetation and other trees in relation to planted trees can lead to competition for resources including, light, water, nutrients, CO_2, O_2, and space. Davis et al. (1999) investigated the effect of herbaceous competition along a water-light-nitrogen gradient and found that seedling survival of two oak species was significantly greater when herbaceous vegetation was removed in the wetter shaded plots. These results are consistent with the results from the present study where secondary species had increased survival and growth in the SAT where competition was reduced and hydrologic stress was less than the FLD cell. Pinto et al. (2012) investigated the effect of moisture stress caused by vegetative competition on three stocktypes of ponderosa pine. The results suggest that small stocktypes had very low survival when exposed to low moisture conditions caused by herbaceous competition, while larger stock had somewhat improved survival. They conclude that appropriate moisture is critical for survival and that herbaceous vegetation competes substantially for moisture. A related finding from the present study was that more species/stocktype combinations had greater survival in the SAT than in the AMB. This suggests that the hydrologic regime and/or reduction in competition in the SAT provided conditions that increased survival which lead to the restoration of ecological structure and functions.

The soil physical and chemical characteristics of the FLD compared to the AMB (higher bulk density, higher clay content, lower soil nutrients) are characteristic of restored wetlands in this region (Bishel-Machung et al. 1996; Shaffer and Ernst 1999; Whittecar and Daniels 1999; Stolt et al. 2000; Campbell et al. 2002; Bruland and Richardson 2005; Daniels and Whittecar 2011). Several studies have found that compacted soil reduces the survival and above- and belowground growth of planted trees (Alberty et al. 1984; Clevland and Kjelgren 1994; Kozlowski 1999; Siegel-Issem et al. 2005) similar to the results of this study. Clay concentrations influence bulk density and have also been shown to negatively affect planted tree growth. Schaff et al. (2003) found that *S. nigra* cuttings (posts) planted in fine-grained sediments (higher silt/clay) compared to coarse-grained sediments in a restored streambank had lower biomass accumulation and leaf area. They hypothesize that the fine-grained sediments prevent root elongation and suggest that soil texture be evaluated prior to restoration. Results from the present study similarly show that increased clay concentrations in conjunction with higher bulk density in the FLD reduced the survival and growth of all seven species.

Several experiments have shown that decreased abundance of soil nutrients has been shown to decrease growth of trees. In a greenhouse experiment investigating the effect of flooding and soil nutrients on *T. distichum* and *Nyssa aquatica* growth Effler and Goyer (2006) found that flooding in combination with low soil nutrients reduced growth, while flooding in combination with fertilization lead to similar growth as trees grown without flooding or fertilization. Day (1987) investigated the effects of flood frequency (no flooding, intermittent flooding and continuous flooding) and nutrient enrichment (no enrichment, nitrogen additions, phosphorus additions and N and P additions) on the biomass production of *Acer rubrum* seedlings within a greenhouse. Continuous flooding reduced biomass production however adding nutrients to the continuously flooded trees increased stem and leaf production. Bailey et al. (2007) found that *B. nigra* planted in a created wetland were larger when planted in areas with higher organic amendments that increased the nutrient content of the soil. While the species and treatments may have varied from previous studies, results from the present study similarly show that low soil nutrient concentrations in combination with hydrologic and competitive stress will reduce the survival and size of planted trees. This suggests that in order to ensure the return of ecological structure and functions associated with planted trees in restored forested wetlands, particular attention should be paid to the initial soil physical and chemical characteristics.

Conclusions

Since the goals of forested wetland restoration are to return ecological structure and functions, including habitat, in created and restored wetlands which often have harsh environmental conditions, we conclude from this study that primary successional species planted using larger containerized stock may return lost ecological structures and habitat functions more quickly than other planting stock. In less stressful environmental conditions, the bare root stocktype grew similarly to the gallon stocktype suggesting that the less expensive bare root stocktype could be used to return a similar amount of ecological structures and functioning as the more expensive gallon stocktype. The tubeling stocktype does not appear to provide added benefit for its intermediate price. Planting primary successional species (especially *S. nigra*) in harsh environmental conditions can improve the return of ecological structure that provides many ecosystem functions including habitat. However, species diversity is an important consideration when attempting to restore forested wetland habitat. Overall, from comparing differences among cells, the results suggest that initial environmental conditions can have a large influence on survival and growth of planted trees. These results could be used for a variety of tree planting situations besides forested wetland restoration including afforestation, reforestation, carbon sequestration, wildlife habitat creation and other conservation projects.

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Tables and Figures

Table 1. Description of environmental parameters for the three types of experimental cells. Numbers represent averages with associated standard deviations.

Environmental Parameter	Ambient	Saturated	Flooded
Hydrology	Recevied only precipitation	Kept saturated for a minimum of 90% of the growing season within the root-zone (10cm) of the plantings and irrigated as needed	Inundated above the root crown for a minimum of 90% of each year
Soil Preparation	Disked and Tilled	Disked and Tilled	Excavated to a depth of 1m (3.1ft.) to an existing clay layer
Herbaceous Vegetation Control	Riding Lawnmower, Push mower, weedwacker, Glyphosate application	Riding Lawnmower, Push mower, weedwacker, Glyphosate application	None
Bulk Density (g/cm^3)	1.03 (0.11)	1.1 (0.13)	1.38 (0.14)
Percent Sand	85.16 (6.16)	88.35 (4.38)	63.74 (10.05)
Percent Silt	10.22 (5.48)	7.57 (3.12)	17.27 (6.44)
Percent Clay	4.62 (1.25)	4.08 (1.5)	18.99 (6.64)
Percent Carbon	1.47 (0.37)	1.2 (0.4)	0.34 (0.12)
Percent Nitrogen	0.17 (0.04)	0.15 (0.04)	0.08 (0.03)
Percent Phosphorus	0.29 (0.08)	0.26 (0.08)	0.18 (0.04)

Table 2. Results of type 3 tests of fixed effects for species and stocktype.

			Survival		Stem Cross-sectional Area at Groundline		Height		Canopy Diameter	
Cell	Source of variation	DF	Wald Chi Square	Pr > F	F-value	Pr > F	F-value	Pr > F	F-value	Pr > F
AMB	Species	6	29.03	0.0014	1.52	<0.001	18.97	<0.001	30.69	<0.001
	Stocktype	2	21.60	<0.001	33.66	<0.001	22.24	<0.001	20.86	<0.001
	Species x Stocktype	12	57.00	<0.001	8.22	<0.001	4.51	<0.001	6.78	<0.001
SAT	Species	6	18.86	0.0038	13.26	<0.001	22.38	<0.001	27.47	<0.001
	Stocktype	2	16.22	<0.001	26.41	<0.001	18.93	<0.001	19.08	<0.001
	Species x Stocktype	12	21.40	0.045	3.67	<0.001	2.42	0.0044	2.10	0.0148
FLD	Species	6	120.89	0.1036	86.01	<0.001	517.61	<0.001	223.65	<0.001
	Stocktype	2	4.53	<0.001	79.34	<0.001	87.35	<0.001	71.23	<0.001
	Species x Stocktype	12	44.77	<0.001	3.42	<0.001	21.91	<0.001	6.67	<0.001

Table 3. Results of type 3 tests of fixed effects for successional group and species.

Cell	Source of variation	DF	Survival Wald Chi Square	Survival Pr > F	Stem Cross-sectional area at Groundline F-value	Stem Cross-sectional area at Groundline Pr > F	Height F-value	Height Pr > F	Canopy Diameter F-value	Canopy Diameter Pr > F
AMB	Succesional Group	1	0.0987	0.7534	103.16	<0.001	61.31	<0.001	59.06	<0.001
	Stocktype	2	45.60	<0.001	6.25	0.002	15.67	<0.001	23.83	<0.001
	Stocktype x Successional Group	2	8.71	0.0128	2.21	0.1104	1.23	0.2929	1.37	0.254
SAT	Succesional Group	1	2.027	0.1545	107.53	<0.001	77.63	<0.001	60.14	<0.001
	Stocktype	2	31.57	<0.001	9.88	<0.001	20.37	<0.001	24.90	<0.001
	Stocktype x Successional Group	2	3.69	0.158	3.29	0.0379	0.6	0.5513	0.74	0.4758
FLD	Succesional Group	1	86.43	<0.001	102.2	<0.001	179.25	<0.001	39.19	<0.001
	Stocktype	2	48.48	<0.001	60.93	<0.001	336.23	<0.001	146.19	<0.001
	Stocktype x Successional Group	2	20.88	<0.001	4.76	0.0088	10.57	<0.001	1.65	0.1923

Table 4. Results of type 3 tests of fixed effects for cell.

				Stem Cross-sectional Area at Groundline		Height		Canopy Diameter	
Species	Stocktype	Source of Variation	DF	F-value	Pr > F	F-value	Pr > F	F-value	Pr > F
B. nigra	Bare root	Cell	54	14.17	<0.0001	69.32	<0.0001	55.53	<0.0001
	Gallon	Cell	107	33.14	<0.0001	148.94	<0.0001	264.74	<0.0001
	Tubeling	Cell	59	39.61	<0.0001	139.69	<0.0001	145.44	<0.0001
L. styraciflua	Bare root	Cell	69	29.12	<0.0001	86.09	<0.0001	80.53	<0.0001
	Gallon	Cell	107	47.87	<0.0001	215.48	<0.0001	241.32	<0.0001
	Tubeling	Cell	39	28.95	<0.0001	57.34	<0.0001	92.33	<0.0001
P. occidentalis	Bare root	Cell	28	2.89	0.1002	12.93	0.0012	9.53	0.0045
	Gallon	Cell	79	11.24	<0.0001	31	<0.0001	29.43	<0.0001
	Tubeling	Cell	53	13.25	<0.0001	19.48	<0.0001	16.17	<0.0001
Q. bicolor	Bare root	Cell	84	3.9	0.024	14.92	<0.0001	15.15	<0.0001
	Gallon	Cell	87	8.39	0.0005	35.09	<0.0001	40.31	<0.0001
	Tubeling	Cell	53	9.92	0.0002	19.71	<0.0001	16.21	<0.0001
Q. palustris	Bare root	Cell	67	6.53	0.0026	7.88	0.0008	10.97	<0.0001
	Gallon	Cell	86	8.63	0.0004	23.14	<0.0001	22.81	<0.0001
	Tubeling	Cell	26	0.26	0.7742	0.29	0.7524	0.61	0.552
Q. phellos	Bare root	Cell	67	3.2	0.0473	10.34	0.0001	8.58	0.0005
	Gallon	Cell	80	16.49	<0.0001	38.69	<0.0001	38.14	<0.0001
	Tubeling	Cell	35	0.36	0.5513	1.49	0.2306	1.53	0.225
S. nigra	Bare root	Cell	51	12.99	<0.0001	54.8	<0.0001	43.67	<0.0001
	Gallon	Cell	111	16.72	<0.0001	55.94	<0.0001	51.08	<0.0001
	Tubeling	Cell	61	8.92	0.0004	61.15	<0.0001	40.97	<0.0001

Table 5. Number of species/measurement combinations that exhibited a particular outcome when comparing stocktypes within each cell. The 28 species/measurement combinations are 7 species paired with each of three morphological measurements (CSAG, H, CD) and survival (e.g. *B. nigra* H, *S. nigra* survival, etc.). The outcomes (>,<,=) result from post-hoc comparisons of stocktypes (BR vs GAL & TB vs GAL & BR vs TB) for each species/measurement combination. Percent represents percentage of occurrence of each outcome for each group of stocktype post-hoc comparisons (e.g. GAL>BR in 60.7% (17) of the 28 post-hoc BR vs. GAL comparisons in the Ambient cell). Total represents sum of outcomes across all cells and percent occurrence of outcomes for groups of post-hoc comparisons. See supplementary material for tables representing comparisons of stocktypes for each individual species/measurements combination.

Outcome	Ambient	Saturated	Flooded	Total
BR < GAL	17 (60.7%)	14 (50%)	25 (89.3%)	56 (66.7%)
BR = GAL	11 (39.3%)	14 (50%)	2 (7.1%)	27 (32.1%)
BR > GAL	0 (0%)	0 (0%)	1 (3.6%)	1 (1.2%)
TB < GAL	22 (78.6%)	21 (75%)	26 (92.9%)	69 (82.1%)
TB = GAL	6 (21.4%)	7 (25%)	2 (7.1%)	15 (17.9%)
TB > GAL	0 (0%)	0 (0%)	0 (0%)	0 (0%)
BR = TB	17 (60.7%)	21 (75%)	20 (71.4%)	58 (69%)
BR > TB	9 (32.1%)	7 (25%)	7 (25%)	23 (27.4%)
BR < TB	2 (7.1%)	0 (0%)	1 (3.6%)	3 (3.6%)

Table 6. Number of stocktype/measurement combinations that exhibited a particular outcome when comparing successional groups within each cell. The 12 stocktype/measurement combinations are 3 stocktypes paired with each of three morphological measurements (CSAG, H, CD) and survival (e.g. BR H, GAL survival, etc.). The outcomes (>,<,=) result from comparison of successional groups (primary vs. secondary) for each stocktype/measurement combination. Percent represents percentage of occurrence of each outcome (e.g. Pri>Sec in 75% (9) of the 12 successional group comparisons in the Ambient cell). Total represents sum of outcomes across all cells and percent occurrence of outcomes for successional group comparisons. See supplementary material for graphs representing comparisons of successional groups for each individual stocktype/measurement combination.

Outcome	Ambient	Saturated	Flooded	Total
Pri>Sec	9 (75%)	12 (100%)	8 (66.7%)	29 (80.6%)
Pri=Sec	2 (16.7%)	0 (0%)	3 (25%)	5 (13.9%)
Pri<Sec	1 (8.3%)	0 (0%)	1 (8.3%)	2 (5.6%)

Table 7. Number of species/stocktype combinations that exhibited a particular outcome when comparing cells for survival and morphological measurements (CSAG, CD, H). The 21 species/stocktype combinations are 7 species paired with BR, GAL and TB stocktypes (e.g. *B. nigra* BR, *S. nigra* TB, etc.). However, due to mortality all 21 combinations are not represented for all comparisons. The outcomes (>,<,=) result from post-hoc comparisons of morphological measurements among cells (AMB vs. SAT, AMB vs. FLD, SAT vs. FLD) for each species/stocktype combinations. Survival was not compared statistically and represents absolute differences. Percent represents percentage of occurrence of each outcome for each group of cell comparisons (e.g. AMB CSAG > SAT CSAG in 47.6% (10) of the 21 post-hoc AMB vs. SAT comparisons). Total represents sum of outcomes across survival and morphological measures and percent occurrence of outcomes for cell groups of post-hoc comparisons. See supplementary material for tables representing comparisons of cells for each individual species/stocktype combination.

Outcome	% Survival	Stem Cross-sectional Area at Groundline	Canopy Diameter	Height	Total
AMB>SAT	6 (28.6%)	10 (47.6%)	9 (42.9%)	17 (81%)	42 (50%)
AMB=SAT	1 (4.8%)	11 (52.4%)	11 (52.4%)	4 (19%)	27 (32.1%)
AMB<SAT	14 (66.7%)	0 (0%)	1 (4.8%)	0 (0%)	15 (17.9%)
AMB>FLD	16 (76.2%)	14 (73.7%)	17 (89.5%)	18 (94.7%)	65 (83.3%)
AMB=FLD	0 (0%)	5 (26.3%)	2 (10.5%)	1 (5.3%)	8 (10.3%)
AMB<FLD	5 (23.8%)	0 (0%)	0 (0%)	0 (0%)	5 (6.4%)
SAT>FLD	16 (76.2%)	10 (52.6%)	16 (84.2%)	14 (73.7%)	56 (71.8%)
SAT=FLD	0 (0%)	9 (47.4%)	3 (15.8%)	5 (26.3%)	17 (21.8%)
SAT<FLD	5 (23.8%)	0 (0%)	0 (0%)	0 (0%)	5 (6.4%)

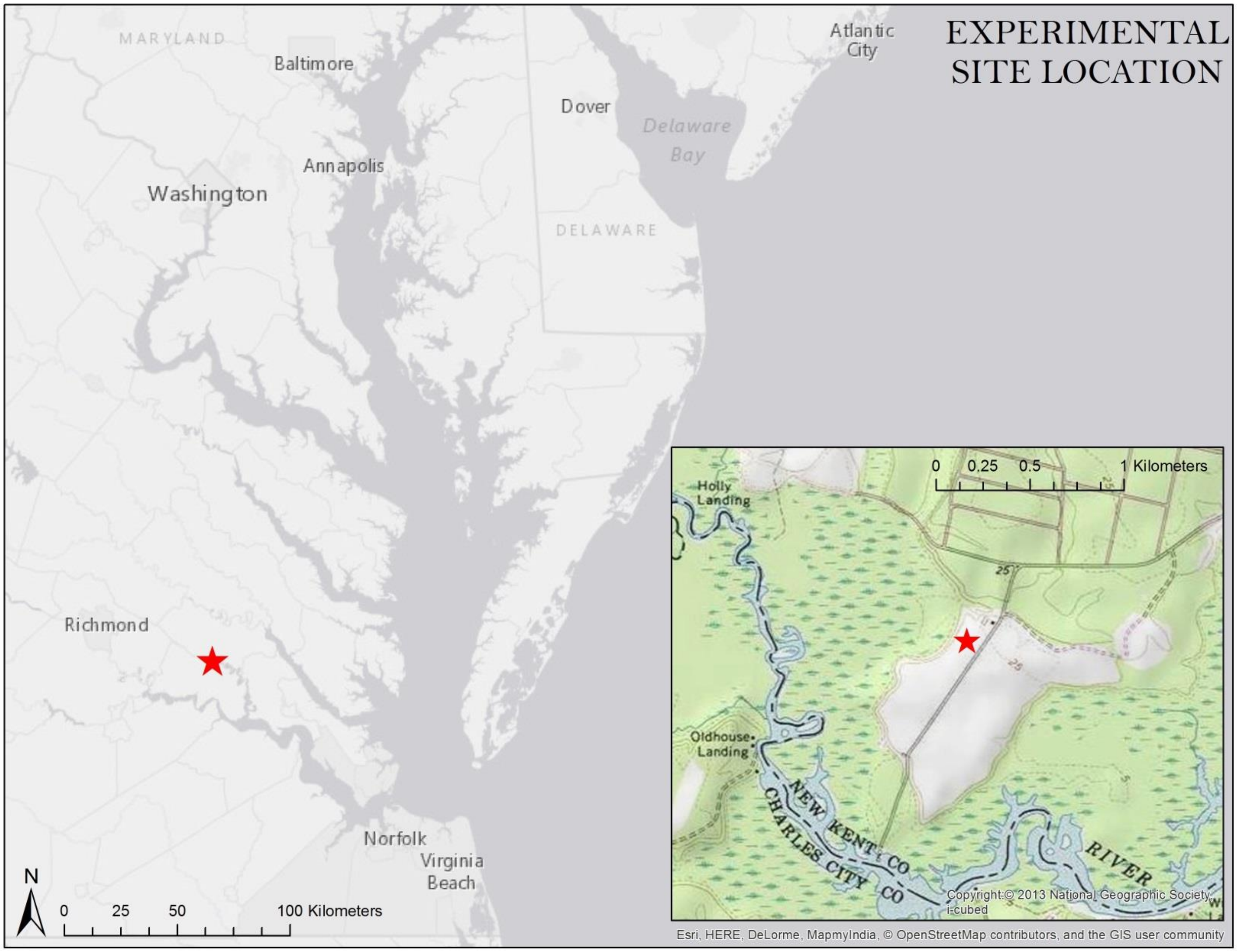

Figure XXX. Experimental site location

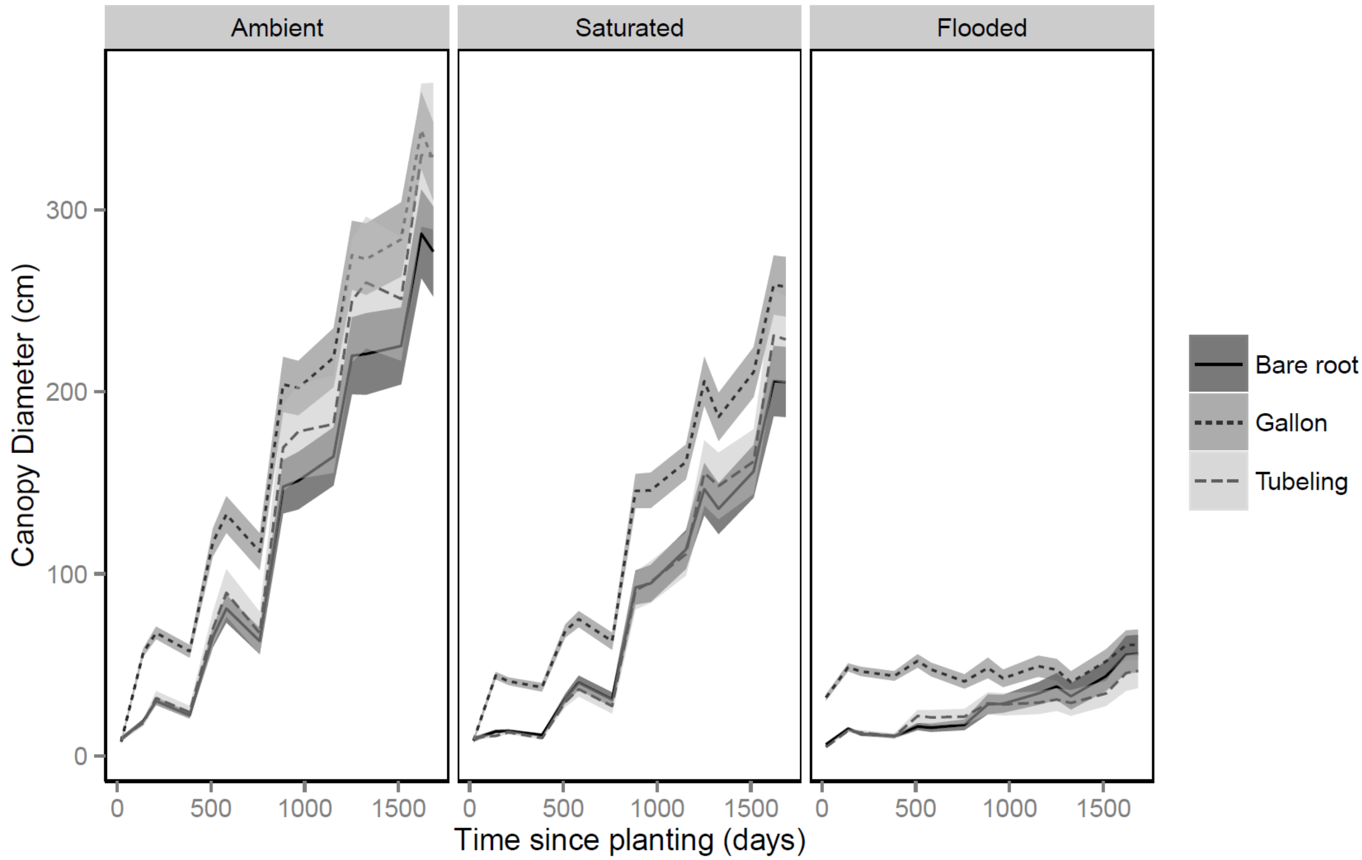

Figure 1. Average crown diameter of stocktypes for three cells. Line represents mean of seven species and ribbons represent 95% confidence interval.

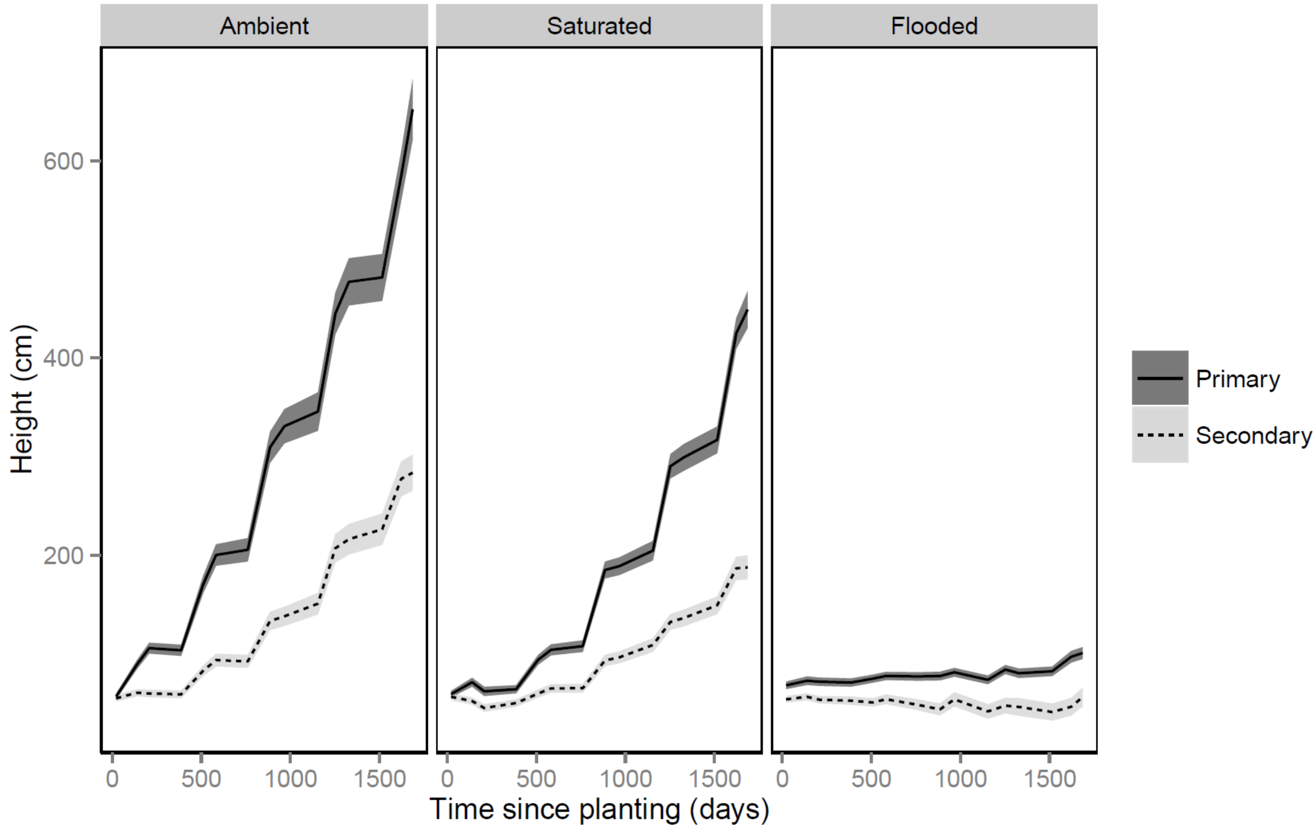

Figure 2. Average height of successional groups for all stocktypes across cells. Line represents mean and ribbons represent 95% confidence interval.

Supplemental Material

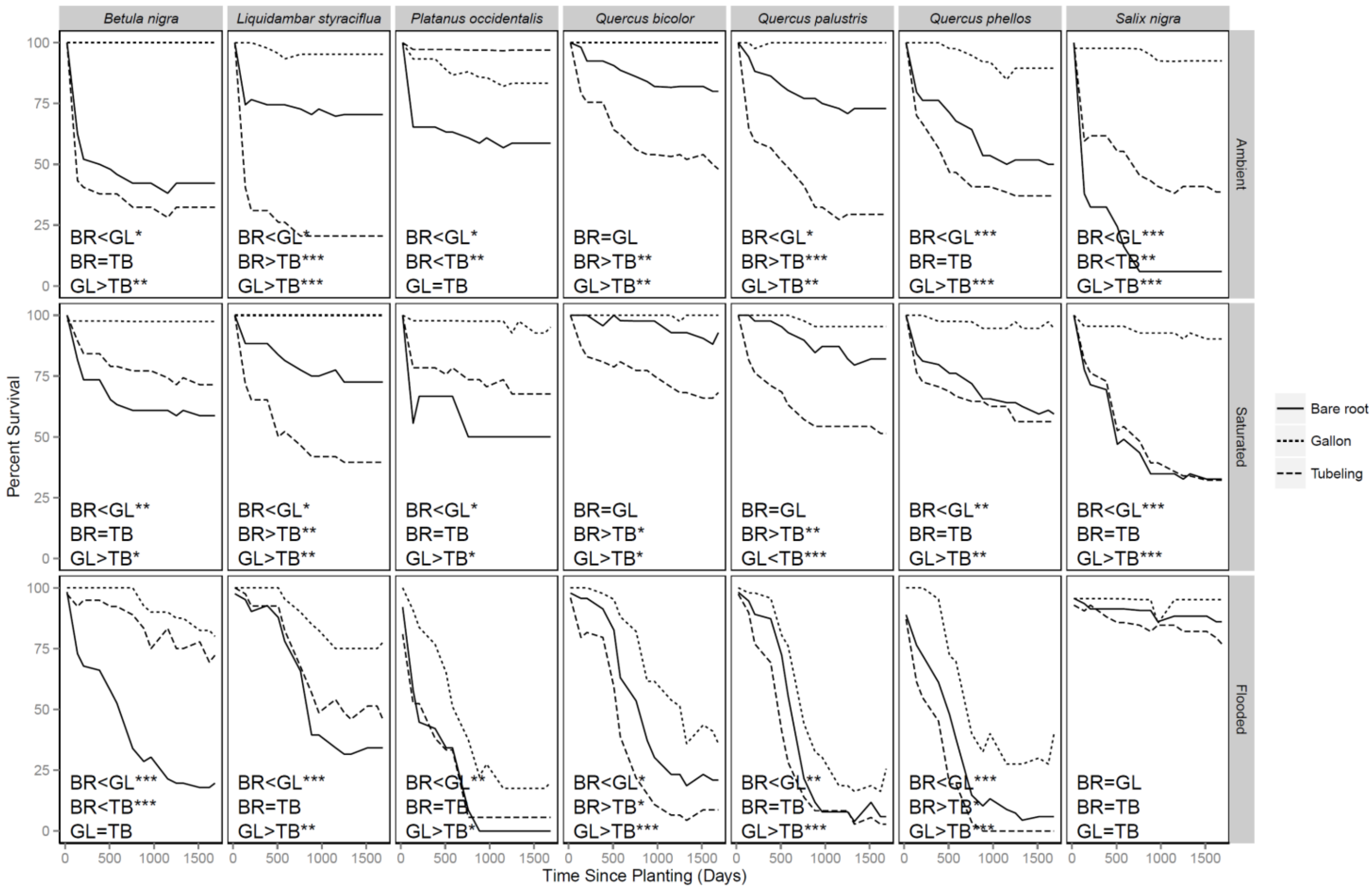

Figure S1. Simple effects model results for survival of stocktypes (lines) among species (columns) and cells (rows). X-axis represents time since planting. For stocktype comparisons, no stars represent no significant difference (p-value > 0.05) while * indicates p-value ≤ 0.05, ** indicates p-value ≤ 0.01 and *** indicates p-value ≤ 0.001.

Table S1. Species exhibiting each outcome within each cell. < and > indicate significant difference in percent survival (See Figure S1). Total represents a count of how many times each outcome occurred across all cells.

Outcome	Ambient	Saturated	Flooded	Total
BR < GAL	*B. nigra, L. styraciflua, P. occidentalis, Q. palustris, Q. phellos, S. nigra*	*B. nigra, L. styraciflua, P. occidentalis, Q. phellos, S. nigra*	*B. nigra, L. styraciflua, P. occidentalis, Q. bicolor, Q. palustris, Q. phellos*	17
BR = GAL	*Q. bicolor*	*Q. bicolor, Q. palustris*	*S. nigra*	4
BR > GAL				0
TB < GAL	*B. nigra, L. styraciflua, Q. bicolor, Q. palustris, Q. phellos, S. nigra*	*B. nigra, L. styraciflua, P. occidentalis, Q. bicolor, Q. palustris, Q. phellos, S. nigra*	*L. styraciflua, P. occidentalis, Q. bicolor, Q. palustris, Q. phellos*	18
TB = GAL	*P. occidentalis*		*B. nigra, S. nigra*	3
TB > GAL				0
BR = TB	*B. nigra, Q. phellos*	*B. nigra, P. occidentalis, Q. phellos, S. nigra*	*L. styraciflua, P. occidentalis, Q. palustris, S. nigra*	10
BR > TB	*L. styraciflua, Q. bicolor, Q. palustris*	*L. styraciflua, Q. bicolor, Q. palustris*	*Q. bicolor, Q. phellos*	8
BR < TB	*P. occidentalis, S. nigra*		*B. nigra*	3

Table S2. Species exhibiting each outcome for three stocktypes. < and > indicate significant difference in percent survival (See Figure S1). Total represents a count of how many times each outcome occurred across all stocktypes.

Outcome	Bare root	Gallon	Tubeling	Total
AMB>SAT	*P. occidentalis*	*B. nigra, Q. palustris, S. nigra*	*P. occidentalis, S. nigra*	6
AMB=SAT		*Q. bicolor*		1
AMB<SAT	*B. nigra, L. styraciflua, Q. bicolor, Q. palustris, Q. phellos, S. nigra*	*L. styraciflua, P. occidentalis, Q. phellos*	*B. nigra, L. styraciflua, Q. bicolor, Q. palustris, Q. phellos*	14
AMB>FLD	*B. nigra, L. styraciflua, P. occidentalis, Q. bicolor, Q. palustris, Q. phellos*	*B. nigra, L. styraciflua, P. occidentalis, Q. bicolor, Q. palustris, Q. phellos*	*P. occidentalis, Q. bicolor, Q. palustris, Q. phellos*	16
AMB=FLD				0
AMB<FLD	*S. nigra*	*S. nigra*	*B. nigra, L. styraciflua, S. nigra*	5
SAT>FLD	*B. nigra, L. styraciflua, P. occidentalis, Q. bicolor, Q. palustris, Q. phellos*	*B. nigra, L. styraciflua, P. occidentalis, Q. bicolor, Q. palustris, Q. phellos*	*P. occidentalis, Q. bicolor, Q. palustris, Q. phellos*	16
SAT=FLD				0
SAT<FLD	*S. nigra*	*S. nigra*	*B. nigra, L. styraciflua, S. nigra*	5

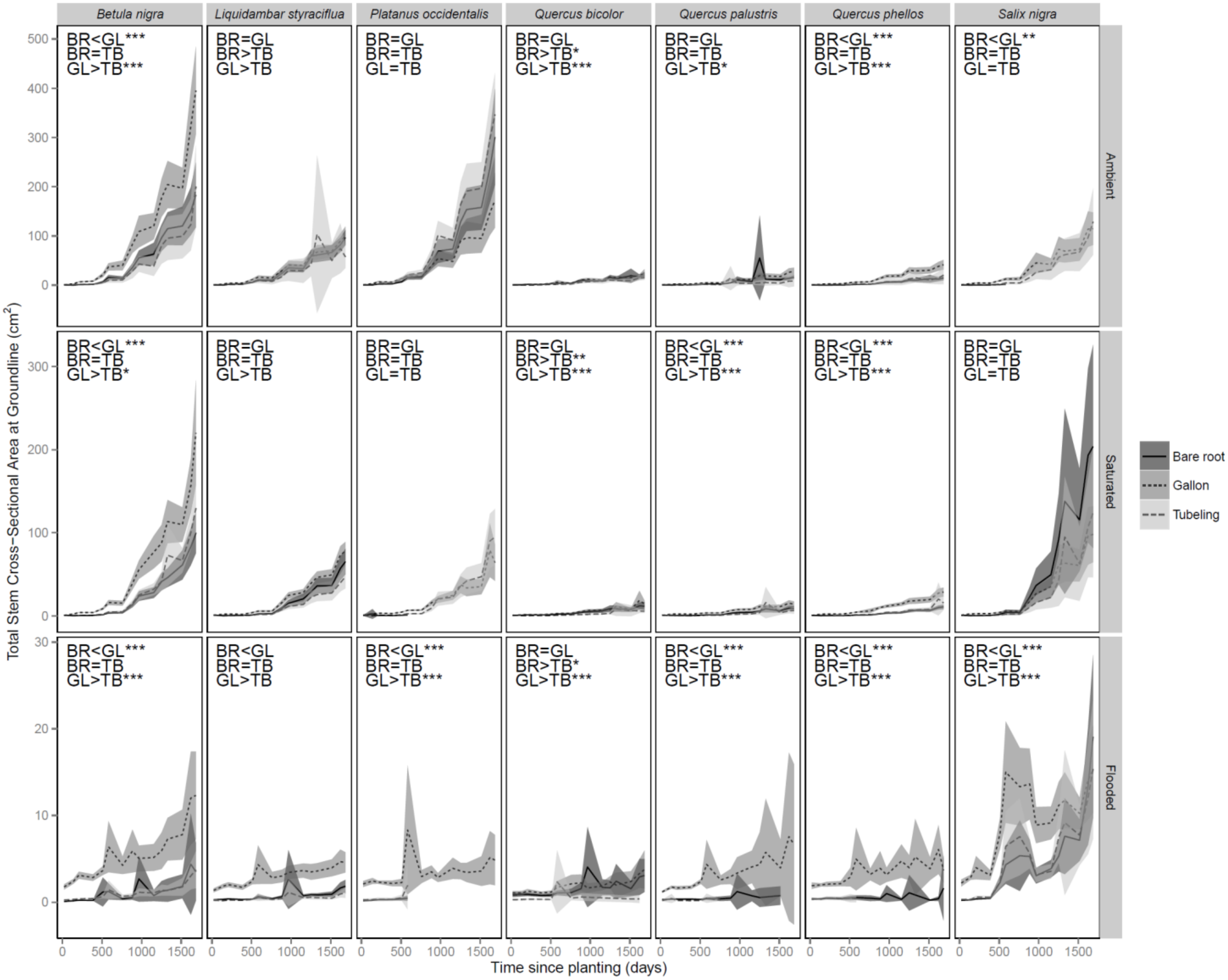

Figure S2. Simple effects model results for CSAG of stocktypes (lines) among species (columns) and cells (rows). X-axis represents time since planting. Ribbons represent 95% confidence interval. Line represents mean. For stocktype comparisons, no stars represent no significant difference (p-value > 0.05) while * indicates p-value ≤ 0.05, ** indicates p-value ≤ 0.01 and *** indicates p-value ≤ 0.001.

Table S3. Number of species exhibiting each outcome within each cell. < and > indicate significant difference in stem cross-sectional area at groundline (CSAG) (See Figure S2). Total represents a count of how many times each scenario occurred across all cells.

Outcome	Ambient	Saturated	Flooded	Total
BR < GAL	*B. nigra, Q. phellos, S. nigra*	*B. nigra, Q. palustris, Q. phellos*	*B. nigra, L. styraciflua, P. occidentalis, Q. palustris, Q. phellos, S. nigra*	12
BR = GAL	*L. styraciflua, P. occidentalis, Q. bicolor, Q. palustris*	*L. styraciflua, P. occidentalis, Q. bicolor, S. nigra*	*Q. bicolor*	9
BR > GAL				0
TB < GAL	*B. nigra, L. styraciflua, Q. bicolor, Q. palustris, Q. phellos*	*B. nigra, L. styraciflua, Q. bicolor, Q. palustris, Q. phellos*	*B. nigra, L. styraciflua, P. occidentalis, Q. bicolor, Q. palustris, Q. phellos, S. nigra*	17
TB = GAL	*P. occidentalis, S. nigra*	*P. occidentalis, S. nigra*		4
TB > GAL				0
BR = TB	*B. nigra, P. occidentalis, Q. palustris, Q. phellos, S. nigra*	*B. nigra, L. styraciflua, P. occidentalis, Q. palustris, Q. phellos, S. nigra*	*B. nigra, L. styraciflua, P. occidentalis, Q. palustris, Q. phellos, S. nigra*	17
BR > TB	*L. styraciflua, Q. bicolor*	*Q. bicolor*	*Q. bicolor*	4
BR < TB				0

Table S4. Number of species exhibiting each outcome for three stocktypes. < and > indicate significant difference in stem cross-sectional area at groundline (CSAG) (See Figure S2). Total represents a count of how many times each scenario occurred across all stocktypes.

Outcome	Bare root	Gallon	Tubeling	Total
AMB>SAT	*B. nigra, L. styraciflua, Q. palustris*	*B. nigra, P. occidentalis, Q. bicolor, Q. palustris*	*B. nigra, P. occidentalis, Q. bicolor*	10
AMB=SAT	*P. occidentalis, Q. bicolor, Q. phellos, S. nigra*	*L. styraciflua, Q. phellos, S. nigra*	*L. styraciflua, Q. palustris, Q. phellos, S. nigra*	11
AMB<SAT				0
AMB>FLD	*B. nigra, L. styraciflua, Q. palustris*	*B. nigra, L. styraciflua, P. occidentalis, Q. bicolor, Q. palustris, Q. phellos, S. nigra*	*B. nigra, L. styraciflua, Q. bicolor, S. nigra*	14
AMB=FLD	*Q. bicolor, Q. phellos, S. nigra*		*P. occidentalis, Q. palustris*	5
AMB<FLD				0
SAT>FLD	*B. nigra, L. styraciflua, S. nigra*	*B. nigra, L. styraciflua, Q. phellos, S. nigra*	*B. nigra, L. styraciflua, S. nigra*	10
SAT=FLD	*Q. bicolor, Q. palustris, Q. phellos*	*P. occidentalis, Q. bicolor, Q. palustris*	*P. occidentalis, Q. bicolor, Q. palustris*	9
SAT<FLD				0

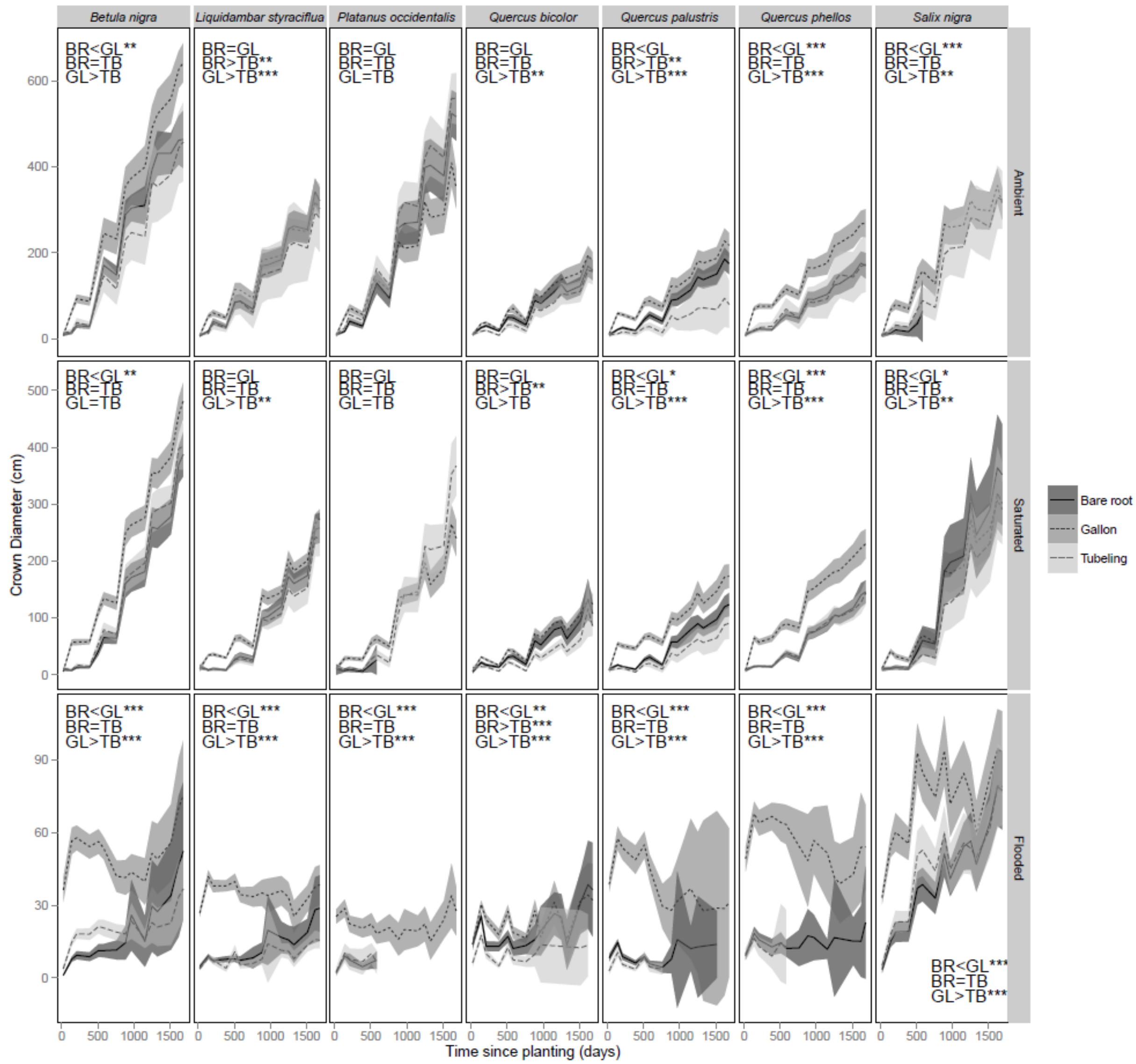

Figure S3. Simple effects model results for CD of stocktypes (lines) among species (columns) and cells (rows). X-axis represents time since planting. Ribbons represent 95% confidence interval. Line represents mean. For stocktype comparisons, no stars represent no significant difference (p-value > 0.05) while * indicates p-value ≤ 0.05, ** indicates p-value ≤ 0.01 and *** indicates p-value ≤ 0.001.

Table S5. Number of species exhibiting each outcome within each cell. < and > indicate significant difference in crown diameter (See Figure S3). Total represents a count of how many times each outcome occurred across all cells.

Outcome	Ambient	Saturated	Flooded	Total
BR < GAL	*B. nigra, Q. palustris, Q. phellos, S. nigra*	*B. nigra, Q. palustris, Q. phellos, S. nigra*	*B. nigra, L. styraciflua, P. occidentalis, Q. bicolor, Q. palustris, Q. phellos, S. nigra*	15
BR = GAL	*L. styraciflua, P. occidentalis, Q. bicolor*	*L. styraciflua, P. occidentalis, Q. bicolor*		6
BR > GAL				0
TB < GAL	*B. nigra, L. styraciflua, Q. bicolor, Q. palustris, Q. phellos, S. nigra*	*L. styraciflua, Q. bicolor, Q. palustris, Q. phellos, S. nigra*	*B. nigra, L. styraciflua, P. occidentalis, Q. bicolor, Q. palustris, Q. phellos, S. nigra*	18
TB = GAL	*P. occidentalis*	*B. nigra, P. occidentalis*		3
TB > GAL				0
BR = TB	*B. nigra, P. occidentalis, Q. bicolor, Q. phellos, S. nigra*	*B. nigra, L. styraciflua, P. occidentalis, Q. palustris, Q. phellos, S. nigra*	*B. nigra, L. styraciflua, P. occidentalis, Q. palustris, Q. phellos, S. nigra*	17
BR > TB	*L. styraciflua, Q. palustris*	*Q. bicolor*	*Q. bicolor*	4
BR < TB				0

Table S6. Number of species exhibiting each outcome for three stocktypes. < and > indicate significant difference in crown diameter (See Figure S3). Total represents a count of how many times each outcome occurred across all stocktypes.

Outcome	**Bare root**	**Gallon**	**Tubeling**	**Total**
AMB>SAT	*L. styraciflua, P. occidentalis, Q. bicolor, Q. palustris*	*B. nigra, P. occidentalis, Q. bicolor, Q. palustris*	*Q. bicolor*	9
AMB=SAT	*B. nigra, Q. phellos*	*L. styraciflua, Q. phellos, S. nigra*	*B. nigra, L. styraciflua, P. occidentalis, Q. palustris, Q. phellos, S. nigra*	11
AMB<SAT	*S. nigra*			1
AMB>FLD	*B. nigra, L. styraciflua, Q. bicolor, Q. palustris, Q. phellos*	*B. nigra, L. styraciflua, P. occidentalis, Q. bicolor, Q. palustris, Q. phellos, S. nigra*	*B. nigra, L. styraciflua, P. occidentalis, Q. bicolor, S. nigra*	17
AMB=FLD	*S. nigra*		*Q. palustris*	2
AMB<FLD				0
SAT>FLD	*B. nigra, L. styraciflua, P. occidentalis, Q. bicolor, Q. palustris, Q. phellos, S. nigra*	*B. nigra, L. styraciflua, P. occidentalis, Q. bicolor, Q. palustris, Q. phellos, S. nigra*	*B. nigra, L. styraciflua, S. nigra*	16
SAT=FLD			*P. occidentalis, Q. bicolor, Q. palustris*	3
SAT<FLD				0

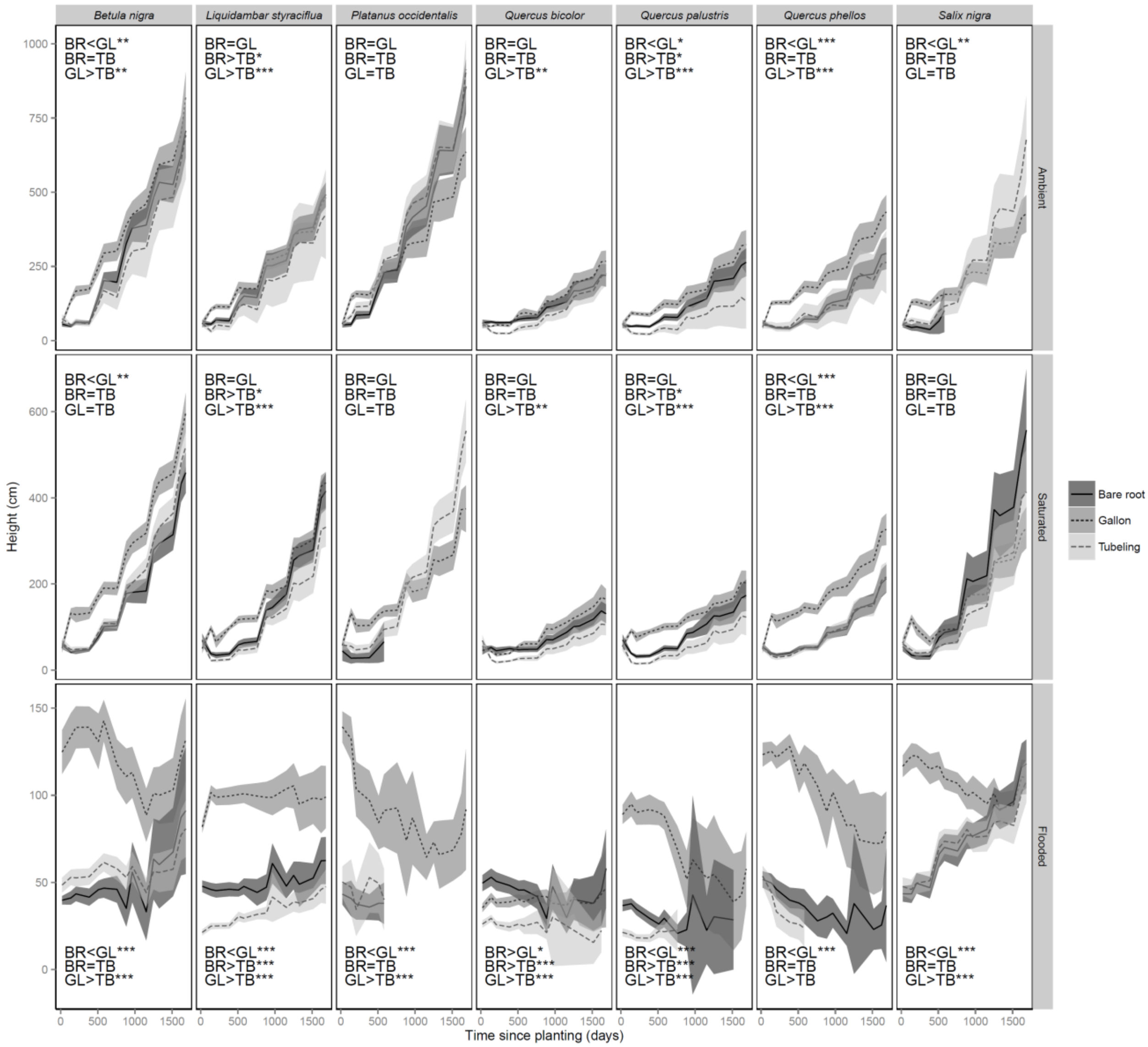

Figure S4. Simple effects model results for H of stocktypes (lines) among species (columns) and cells (rows). X-axis represents time since planting. Ribbons represent 95% confidence interval. Line represents mean. For stocktype comparisons, no stars represent no significant difference (p-value > 0.05) while * indicates p-value ≤ 0.05, ** indicates p-value ≤ 0.01 and *** indicates p-value ≤ 0.001.

Table S7. Number of species exhibiting each outcome within each cell. < and > indicate significant difference in height (See Figure S4). Total represents a count of how many times each outcome occurred across all cells.

Outcome	Ambient	Saturated	Flooded	Total
BR < GAL	*B. nigra, Q. palustris, Q. phellos, S. nigra*	*B. nigra, Q. phellos*	*B. nigra, L. styraciflua, P. occidentalis, Q. palustris, Q. phellos, S. nigra*	12
BR = GAL	*L. styraciflua, P. occidentalis, Q. bicolor*	*L. styraciflua, P. occidentalis, Q. bicolor, Q. palustris, S. nigra*		8
BR > GAL			*Q. bicolor*	1
TB < GAL	*B. nigra, L. styraciflua, Q. bicolor, Q. palustris, Q. phellos*	*L. styraciflua, Q. bicolor, Q. palustris, Q. phellos*	*B. nigra, L. styraciflua, P. occidentalis, Q. bicolor, Q. palustris, Q. phellos, S. nigra*	16
TB = GAL	*P. occidentalis, S. nigra*	*B. nigra, P. occidentalis, S. nigra*		5
TB > GAL				0
BR = TB	*B. nigra, P. occidentalis, Q. bicolor, Q. phellos, S. nigra*	*B. nigra, P. occidentalis, Q. bicolor, Q. phellos, S. nigra*	*B. nigra, P. occidentalis, Q. phellos, S. nigra*	14
BR > TB	*L. styraciflua, Q. palustris*	*L. styraciflua, Q. palustris*	*L. styraciflua, Q. bicolor, Q. palustris*	7
BR < TB				0

Table S8. Number of species exhibiting each outcome for three stocktypes. < and > indicate significant difference in height (See Figure S4). Total represents a count of how many times each outcome occurred across all stocktypes.

Outcome	Bare root	Gallon	Tubeling	Total
AMB>SAT	*B. nigra, L. styraciflua, P. occidentalis, Q. bicolor, Q. palustris, Q. phellos*	*B. nigra, L. styraciflua, P. occidentalis, Q. bicolor, Q. palustris, Q. phellos, S. nigra*	*B. nigra, P. occidentalis, Q. bicolor, S. nigra*	17
AMB=SAT	*S. nigra*		*L. styraciflua, Q. palustris, Q. phellos*	4
AMB<SAT				0
AMB>FLD	*B. nigra, L. styraciflua, Q. bicolor, Q. palustris, Q. phellos, S. nigra*	*B. nigra, L. styraciflua, P. occidentalis, Q. bicolor, Q. palustris, Q. phellos, S. nigra*	*B. nigra, L. styraciflua, P. occidentalis, Q. bicolor, S. nigra*	18
AMB=FLD			*Q. palustris*	1
AMB<FLD				0
SAT>FLD	*B. nigra, L. styraciflua, Q. phellos, S. nigra*	*B. nigra, L. styraciflua, P. occidentalis, Q. bicolor, Q. palustris, Q. phellos, S. nigra*	*B. nigra, L. styraciflua, S. nigra*	14
SAT=FLD	*Q. bicolor, Q. palustris*		*P. occidentalis, Q. bicolor, Q. palustris*	5
SAT<FLD				0

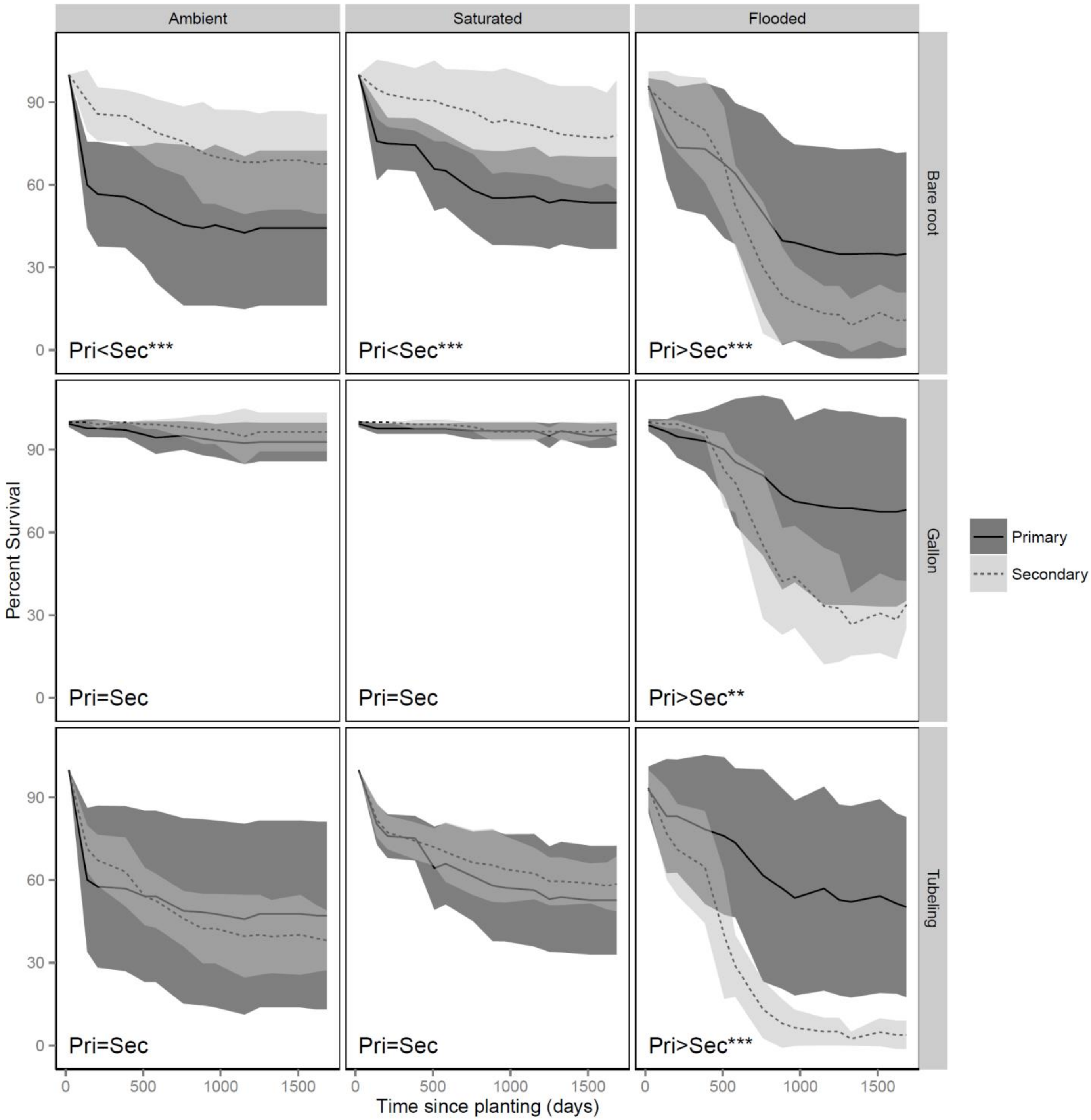

Figure S5. Simple effects model results for survival (time until death) of successional group (lines) among cells (columns) and stocktype (rows). Ribbons represent 95% confidence interval. Line represents mean. For successional group comparisons, no stars represent no significant difference (p-value > 0.05) while * indicates p-value ≤ 0.05, ** indicates p-value ≤ 0.01 and *** indicates p-value ≤ 0.001.

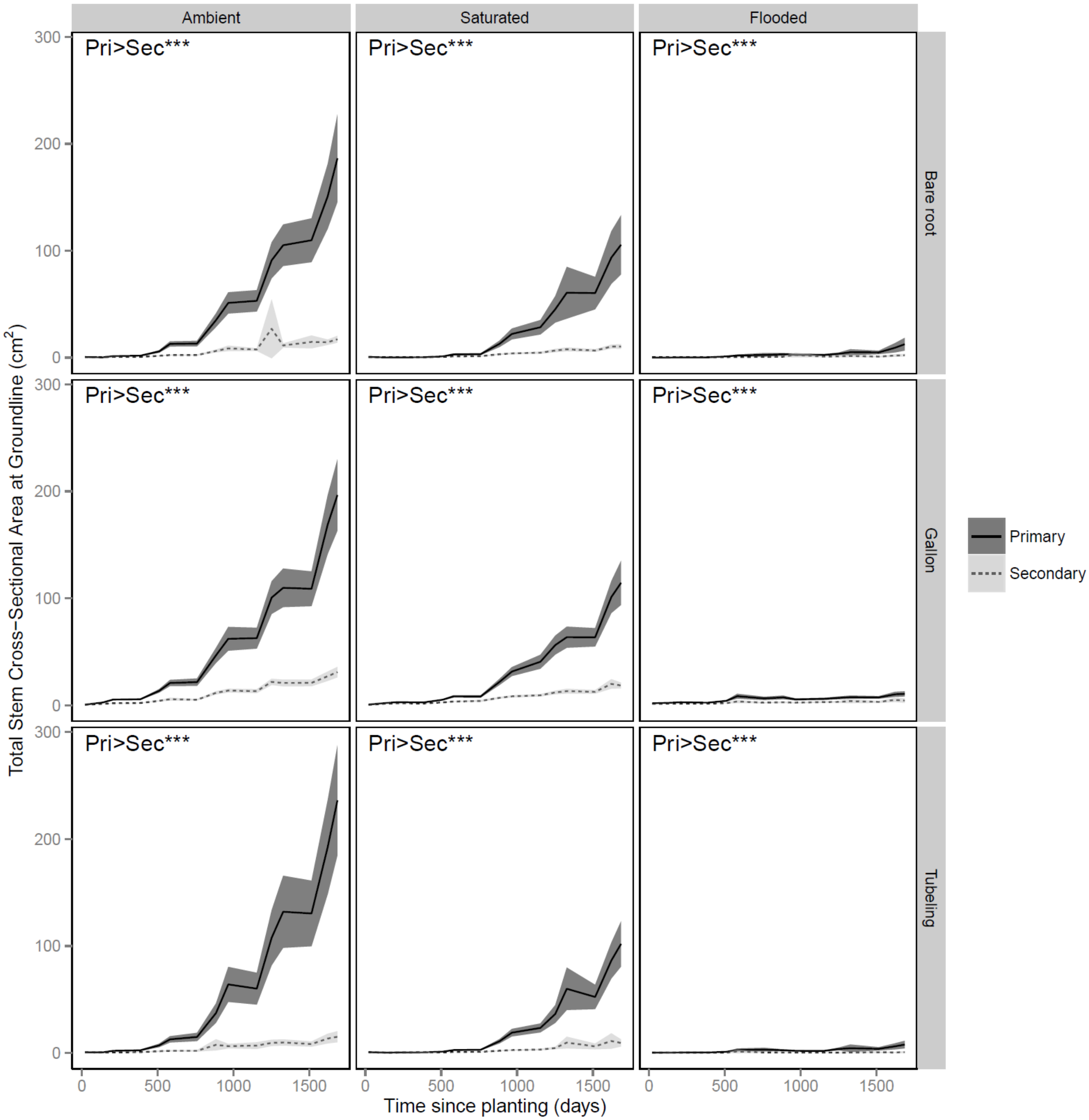

Figure S6. Simple effects model results for CSAG of successional group (lines) among cells (columns) and stocktype (rows). Ribbons represent 95% confidence interval. Line represents mean. For successional group comparisons, no stars represent no significant difference (p-value > 0.05) while * indicates p-value ≤ 0.05, ** indicates p-value ≤ 0.01 and *** indicates p-value ≤ 0.001.

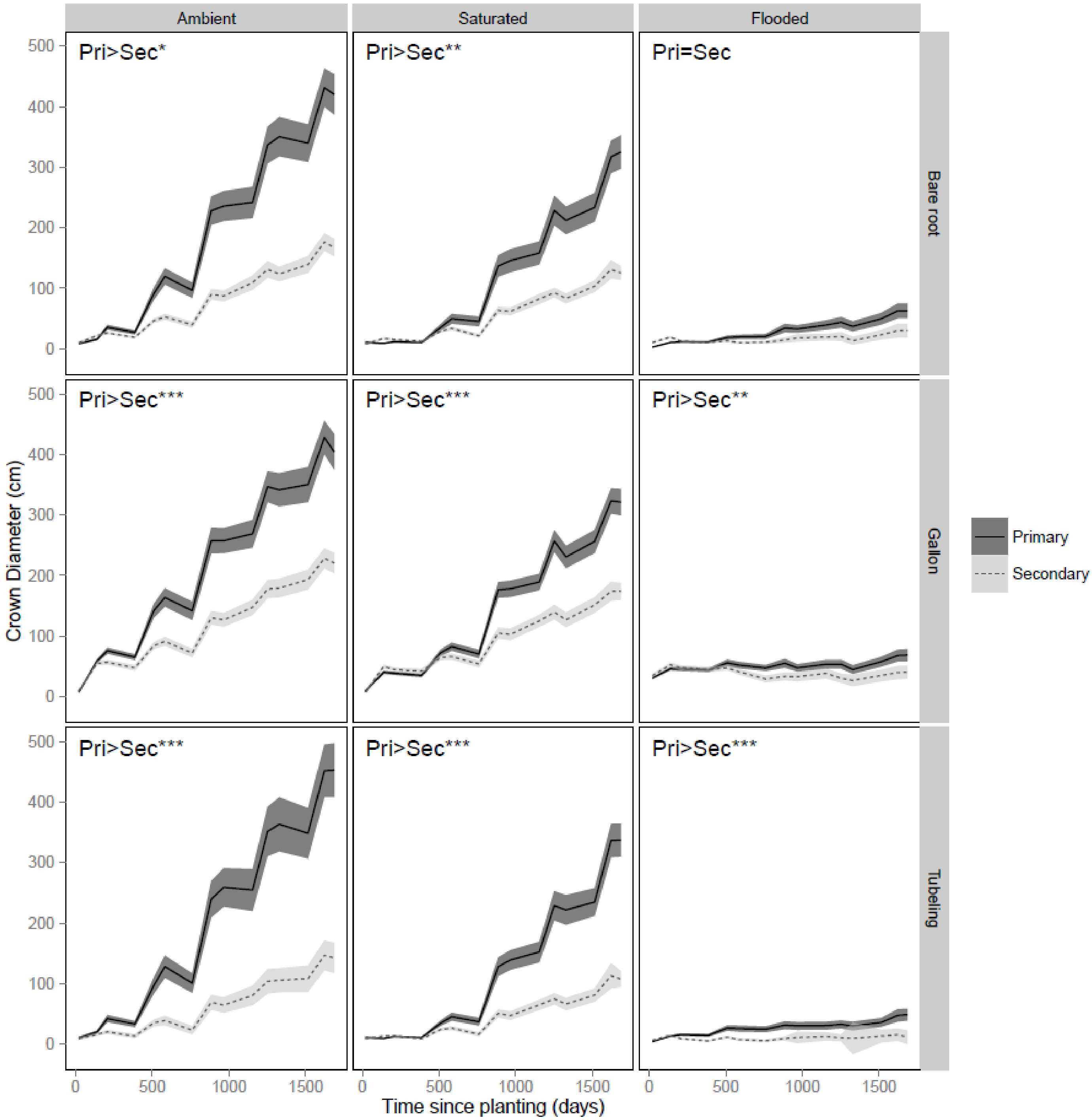

Figure S7. Simple effects model results for CD of successional group (lines) among cells (columns) and stocktype (rows). Ribbons represent 95% confidence interval. Line represents mean. For successional group comparisons, no stars represent no significant difference (p-value > 0.05) while * indicates p-value ≤ 0.05, ** indicates p-value ≤ 0.01 and *** indicates p-value ≤ 0.001.

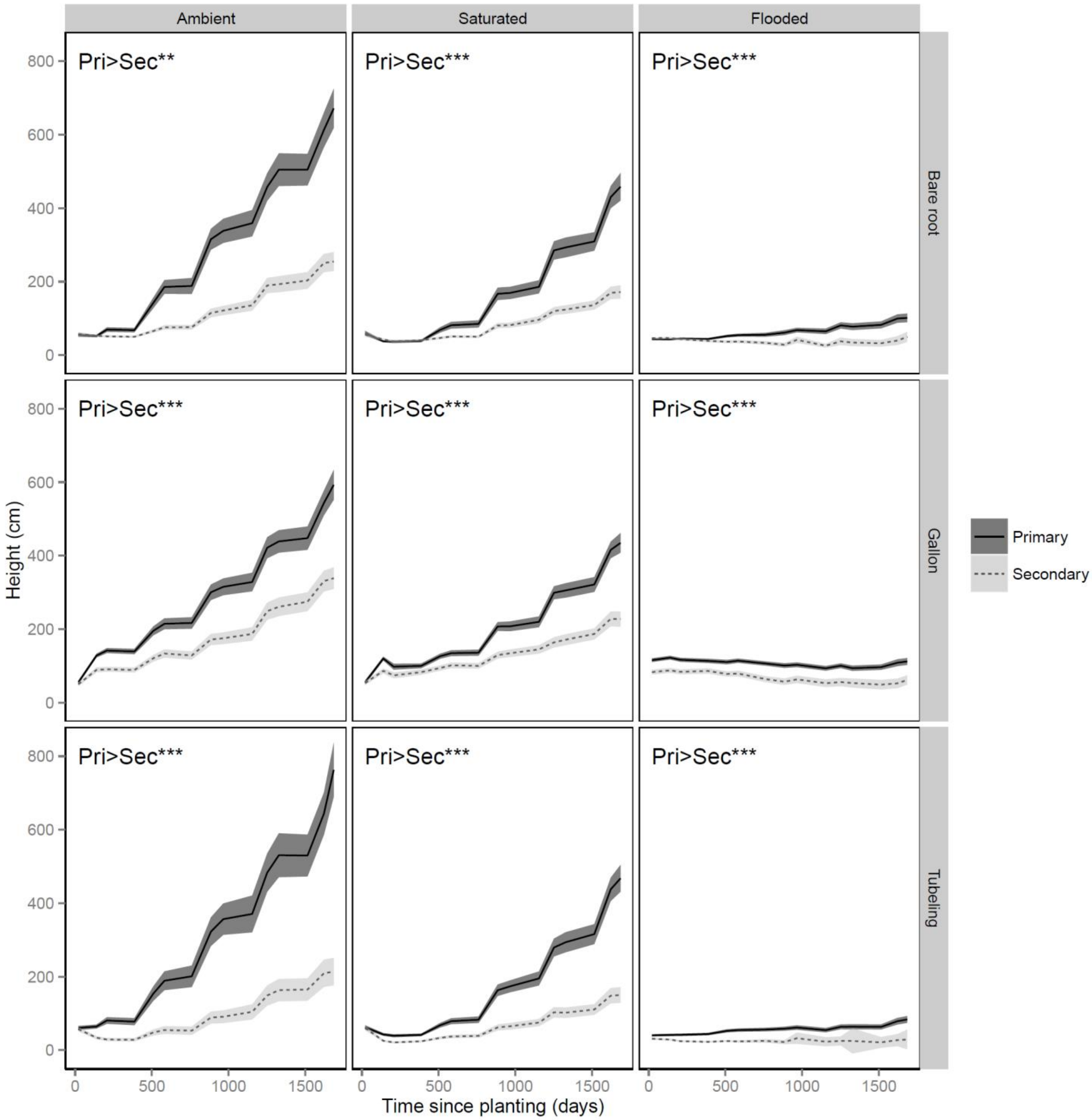

Figure S8. Simple effects model results for H of successional group (lines) among cells (columns) and stocktype (rows). Ribbons represent 95% confidence interval. Line represents mean. For successional group comparisons, no stars represent no significant difference (p-value > 0.05) while * indicates p-value ≤ 0.05, ** indicates p-value ≤ 0.01 and *** indicates p-value ≤ 0.001.