Influences of Soil Amendments and Microtopography on Vegetation at a Created Tidal Freshwater Swamp in Southeastern Virginia

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Abstract: Influences of Soil Amendments and Microtopography on Vegetation at a Created Tidal Freshwater Swamp in Southeastern Virginia

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The purpose of this study was to determine the effects of amendments (control, (1x) compost, (2x) compost, (TS) topsoil, and 1x+TS) and microtopography (level, pit and mound) on three parameters (plant species composition, above-ground characteristics of *Taxodium distichum*, and plant root characteristics) of vegetation growing at a created tidal freshwater swamp in Virginia. None of the soil treatments met the traditional vegetation criteria for federal wetland jurisdictional determination, which only considers dominant species. When the same criteria were used for all of the species, the control, 1x, and 2x treatments met jurisdictional criteria. Considering these findings, vegetative criteria should be re-evaluated for young created wetlands. Compost addition produced the highest proportion of obligate wetland species (30%) while topsoil additions created the lowest proportion of wetland obligates (11%) and the highest proportion of upland plants. The 1x treatment generated the greatest species evenness and lowest weighted average (2.57). Topsoil treatments had the lowest diversity and evenness. Therefore, compost amendment is recommended to increase hydrophytes without compromising evenness and diversity. Bald cypress in pits were taller, had larger trunk diameter and basal trunk swelling than trees growing at higher elevations. Roots growing in mounds were more numerous with greater length than roots at lower elevations. Root length and count were highest for the control soil treatment. Amended treatments may have had lower rooting values because nutrient supply was adequate. Overall, incorporating microtopography and compost during wetland creation had a positive effect on vegetative function in this system.

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1 Introduction

Wetland Mitigation, Construction and Challenges

Unfortunately, the continued destruction or disturbance of wetlands is inevitable as population and land-use pressures increase, particularly in our coastal regions where wetlands are common. In these situations, mitigation of impacts to wetlands is mandatory. Wetland mitigation is a step-wise process to ameliorate human impacts to wetlands and their functions. Avoidance, minimization, onsite restoration and finally, off-site creation, are the required sequential steps, with off-site creation of new constructed wetlands only being allowed if the other options such as avoidance or minimization of impact are shown to be impossible or not economically viable.

The purpose of off-site creation is to compensate for the loss of function of the destroyed wetlands on land that was not previously a wetland, and it is the most difficult type of wetland mitigation to successfully accomplish (Zedler and Callaway 1999). Many off-site created wetlands involve excavating and/or removing the soil so that new ground elevation is within 25 cm or less of the water table during the growing season to meet hydrology requirements for a jurisdiction (see section 1.1).

In Virginia, for a constructed wetland site to meet permit release conditions (which usually takes 5-10 years), the U.S. Army Corps of Engineers (USCOE) and Virginia Department of Environmental Quality (DEQ) evaluate the constructed wetland using the same three characteristics that are used to determine jurisdictional wetlands (for the specific criteria for a jurisdictional wetland, see section 1.1), namely the presence of wetland hydrology, hydric soils, and hydrophytic vegetation. While hydrology (water level relative to soil surface) has the largest influence on wetland processes (Mitsch and Gosselink 1993), vegetation and hydric soils are more permanent features in the landscape, and their presence can signify appropriate wetland hydrology (Day and Megonigal 1993). All three characteristics are inter-related and can influence one another. For example, hydrology influences the type of vegetation (hydrophytes or upland) that can grow at a site and also the chemical reactions such as reduction and oxidation which take place in the soil. Vegetation also influences the hydrology via transpiration (especially trees) and soil properties via contribution of organic material.

Originally, one of the primary assumptions of wetland creation designs was that if the soil elevation was simply lowered down to within close proximity to the water table, the rest of the system (e.g. plants, animals, soil redox, and habitat) would develop within a short time period. While hydrology is the most important feature in wetland design (Mitsch and Gosselink 1993), this general approach and practice has been proven ineffective in many cases. Campbell *et al.* (2002) summed up the situation perfectly by writing, "physical resemblance may or may not lead to functional replacement."

In 2000, the National Academy of Sciences concluded that "The goal of no net loss of wetlands is not being met for wetland functions by the mitigation program." Wetland functions include everything from flood mitigation, improving water quality, plant productivity, animal habitat, and recreation. Created wetlands often do not perform these valuable functions as well as natural wetlands. Atkinson (1991) observed a large wetland compensation site in Charles City County, Virginia and found that there was a loss of function due to lack of reducing conditions, compaction and lack of organic material. Typical wetland creation practices such as the excavation of the upper soil layers remove the topsoil and natural microtopography. Oftentimes, the topsoil horizon is not replaced due to the impracticality and/or expense, and therefore, the seed bank and organic materials are lost. The removal of viable seeds from the native seed bank likely slows the recovery of wetland vegetation and desirable species may not reestablish before more aggressive early successional species move in (Brown and Bedford 1997). Moreover, the large and heavy equipment performing excavation severely compacts the soil. As a result of these practices, created wetland soils often contain less organic matter, have higher bulk densities, and a greater percentage of upland plant species in comparison to natural wetlands (Campbell *et al.* 2002). Because of this presumed loss of function, constructed forested wetlands are subject to higher mitigation ratios which can be anywhere from 2:1 up to 5:1 (mitigation: disturbance) in Virginia, depending on the type of wetland being replaced. For example, for every 1 ha of disturbed forested wetland, 2-5 ha would need to be replaced.

According to Campbell *et al.* (2002) successful wetland creation involves "proper planning, construction, and the introduction of appropriate biotic material should initiate natural processes which continue indefinitely in a successful wetland creation project, with minimal human input." Many studies indicate that reapplication of micro-topography, and addition of native topsoil or compost are influential factors in encouraging natural wetland functions in constructed wetlands (Cummings 1999, Whittecar and Daniels 1999, Stolt *et al.* 2001, Bergschneider 2005). The use of topsoil and compost can serve to initiate and maintain certain natural functions because they serve as a foundation for vegetative growth, microbial colonization, and biochemical processes (Brinson and Rheinhardt 1996). In a study comparing 33 created herbaceous wetlands in west-central Florida (with and without topsoil added), Anderson and Cowell (2004) found that initial mulching was still affecting the wetland ecosystem development 5-10 years after their construction. This overall study focused on the effects of microtopography and soil treatments on wetland vegetation in a created tidal freshwater wetland in a statistically designed field experiment.

Literature Review

1.1 Wetlands: History, Importance and Protection

The most widely used definition for wetlands is “Those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas” (Environmental Laboratory 1987). In order to legally determine the presence of a wetland, experts use modified criteria as originally set forth in the 1987 Corps of Engineers Wetland Delineation Manual (Environmental Laboratory 1987). This manual uses the simultaneous presence of three criteria: 1) wetland hydrology, 2) hydric soils, and 3) a dominance of hydrophytic vegetation to determine if the land in question is indeed a jurisdictional wetland and therefore protected by Section 404. Specifically, these criteria are:

- **Wetland Hydrology Criteria** from Environmental Laboratory (1987):

  The area must be inundated or saturated near the surface (30-50 cm depending on soil texture) for 5% of the growing season (which is the portion of the year when the soil temperature 50 cm below the surface is above 5^{o} C) in an extremely wet landscape and 12.5% of the growing season in a marginally wet landscape. Primary indicators of wetland hydrology include: drainage patterns, drift lines, sediment deposition, watermarks, stream gage data, well data, and visual observation of saturated soils or inundation. If one or more of these primary indicators is present, the site meets the requirements for wetland hydrology. If a primary indicator is not present, the site can still meet the wetland hydrology criteria if two secondary indicators are present. The secondary indicators are: presence of oxidized rhizospheres in the upper 30 cm of soil, water stained leaves, local soil survey hydrology data for identified soils, or a positive FAC-neutral test (see chapter 3) for vegetation.

- **Hydric Soil Criteria** from Natural Resources Conservation Service (2003):

1. "All Histels except Folistels and Histosols except Folists, or
2. Soils in Aquic suborders, great groups, or subgroups, Albolls suborder, Historthels great group, Histoturbels great group, Pachic subgroups, or Cumulic subgroups that are:

    a. Somewhat poorly drained with a water table equal to 0.0 foot (ft) from the surface during the growing season, or

    b. poorly drained or very poorly drained and have either:

        i. water table equal to 0.0 cm during the growing season if textures are coarse sand, sand, or fine sand in all layers within 50 cm, or for other soils,

        ii. water table at less than or equal to 15 cm from the surface during the growing season if permeability is equal to or greater than 15 cm/hour in all layers within 50 cm, or

iii. water table at less than or equal to 30 cm from the surface during the growing season if permeability is less than 15 cm/hour in any layer within 50 cm, or

3. Soils that are frequently ponded for long duration or very long duration during the growing season, or
4. Soils that are frequently flooded for long duration or very long duration during the growing season."

A variety of conditions such as climate, soil color, parent material and soil texture can influence the presence or absence of these indicators and the guidelines which can be used to determine the presence of hydric soils, and one should refer to "Field Indicators of Hydric Soils in the United States" (Hurt and Carlisle 2001) for more specific guidelines.

- **Hydrophytic Vegetation Criteria**:

  More than 50% of the dominant species are categorized as: Obligate wetland, Facultative wetland, or Facultative (see Table 1 for more information on these categories). Other indicators to strengthen the case of hydrophytic vegetation include the visual observation of plant species growing in areas of prolonged inundation or saturation; and the presence of morphological, physiological or reproductive adaptations to flooded or saturated conditions. (Environmental Laboratory 1987)

Table 1. Plant Indicator Status Categories* (Environmental Laboratory 1987).

Indicator Category	**Indicator Symbol**	**Definition**
Obligate Wetland Plants	OBL	Plants that occur almost always (estimated probability >99 percent) in wetlands under natural conditions, but which may also occur rarely (estimated probability <1 percent) in nonwetlands. Examples: *Spartina alterniflora*, *Taxodium distichum*.
Facultative Wetland	FACW	Plants that occur usually (estimated probability >67 percent to 99 percent) in wetlands, but also occur (estimated probability 1 percent to 33 percent) in nonwetlands. Examples: *Fraxinus pennsylvanica, Cornus stolonifera*.
Facultative Plants	FAC	Plants with a similar likelihood (estimated probability 33 percent to 67 percent) of occurring in both wetlands and nonwetlands. Examples: *Gleditsia triacanthos*, *Smilax rotundifolia*.
Facultative Upland	FACU	Plants that occur sometimes (estimated probability 1 percent to <33 percent) in wetlands, but occur more often (estimated probability >67 percent to 99 percent) in nonwetlands. Examples: *Quercus rubra*, *Potentilla arguta*.
Obligate Upland Plants	UPL	Plants that occur rarely (estimated probability <1 percent) in wetlands, but occur almost always (estimated probability >99 percent) in nonwetlands under natural conditions. Examples: *Pinus echinata*, *Bromus mollis*.

* The five categories are further subdivided by (+) (considered to be wetter) and (-) (considered to be drier) modifiers.

Before the mid 1970's, the destruction of wetlands was an accepted and encouraged practice in the United States. During this time, wetlands were seen as inhospitable, mysterious, disease causing and useless pieces of land. Indeed, the Swamp Lands Acts of 1849, 1850 and 1860 encouraged the drainage of wetlands in 15 western states (Mitsch and Gosselink 1993). In a wetland survey comparison from pre-settlement to the mid-1980's, more than half (53%) of the wetlands in the conterminous United States had been lost (Dahl 1990, Mitsch and Gosselink 1993). In fact, the state of Virginia lost an estimated 42% of its wetlands during this time (Dahl 1990, Mitsch and Gosselink 1993). Currently, the worldwide estimate for wetland loss due to human activity is 50% (Zedler and Kercher 2005).

Scientists, environmentalists and many others have worked to reverse society's negative views of wetlands and to reveal the contributions that wetland ecosystems provide. Wetlands cover less than 3% of the earth, but they contribute up to 40% of global annual renewable ecosystem resources with water quality ranking highest (Zedler and Kercher 2005). These ecosystems are described as "kidneys of the landscape" and "biological supermarkets"(Mitsch and Gosselink 1993). In addition, wetlands are some of the most productive ecosystems on earth. Wetlands perform also provide significant benefits to society such as: improving water quality, flood mitigation, nutrient and contaminant trapping, protecting shorelines, and recharging groundwater (Cronk and Fennessy 2001). Due to wetland destruction and alteration, large amounts of sediments and nutrients bypass coastal marshes in the lower Mississippi and end up in the Gulf of Mexico resulting in dead zones (Rabalais *et al.* 2000). Wetlands also provide habitat for a wide variety of plants and animals, yield an assortment of economically valuable products and provide recreation such as hunting, hiking, and kayaking.

Because of the substantial economic and social values of wetlands mentioned above, a range of regulations have been enacted to protect them from further destruction. Many states and local governments have enacted their own wetland protection acts, but the main federal (USA) law protecting wetlands is Section 404 of the Clean Water Act (Mitsch and Gosselink 1993). Section 404 promulgates a permit program which regulates dredging and filling of jurisdictional wetlands and other waters of the United States and is enforced by the U.S. Army Corps of Engineers (COE).

1.2 Created vs. Natural Wetlands

Many authors have questioned the notion that created wetlands will function similarly to the natural wetlands they replace (Langis *et al.* 1991, Reinartz and Warne 1993, Gibson *et al.* 1994, Shaffer and Ernst 1999, Zedler and Callaway 1999, Stolt *et al.* 2000, Zedler and Callaway 2000, Cole *et al.* 2001, Stolt *et al.* 2001, Zedler *et al.* 2001, Zedler and Kercher 2005). Measures of wetland function in relation to plant growth include the status of: topography, absence of invasive species, plant growth, revegetation, habitat type, nutrient supplies, seed banks, plant canopy, seedling survival, increased biodiversity, decomposition rates, patterns of succession, seedling competition, and avoidance of soil erosion (Teal and Peterson 2005).

Young created wetlands have different vegetative structure from the wetlands they are intended to replace, and these differences in structure result in differences in function such as habitat provisions for certain species and groups. For example, in a soil amendment study by Gibson, *et al*. (1994), a created cordgrass (*Spartina foliosa* Trin.) marsh failed to attract the Light-footed Clapper Rail (*Rallus longirostris levipes*) to nest. Nesting by this bird is an important wildlife function of cordgrass marshes, and the created marsh was a failure because it did not provide adequate plant canopy architecture for this to occur. Though the above-ground biomass and stem densities of cordgrass were proportional to the amount of N added to the soil in the creation site, the created wetland still did not achieve functional equivalency because plant height was half that of the natural wetland. The authors recommended repeated applications of N, but still questioned if wetland losses could be adequately replaced by wetland creation.

In another study, Cole *et al.* (2001) found similar biomass between natural and created wetlands, but a difference in community structure was noted. In the natural wetlands, biomass was spread among many species, but created wetlands were primarily clonal dominated by plant species such as *Typha latifolia* L. or *Phalaris arundinacea* L., which are both considered to be invasive species. Balcombe *et al.* (2005) found that species richness, evenness, and diversity were actually greater in mitigation wetlands but that there were major differences in species composition. Mitigation sites had more pioneer species, non-native dominants and species with lower conservation quality. When comparing vegetation growing in a created wetland to a natural wetland, Heaven *et al.* (2003) found that 65% of the plants in the natural site were obligate wetland species while the created wetland only supported 34% obligates. More upland species were found in the created wetland as well.

A study investigating root growth differences between natural and restored wetlands Rodgers *et al.* (2004) found that below-ground C inputs from fine roots were significantly less at the restoration site in comparison to the natural site. At the 31-60 cm depth range, the restoration site mean root diameter was half that of natural sites. They also reported that root length density was more seasonally variable in restoration sites than in natural sites.

1.3 Tidal Freshwater Swamps (Forested Wetlands)

Tidal freshwater swamps are wetlands that are affected by tidal fluctuations, but are inland enough such that their surface water is low in salinity (< 0.5 ppt). This low salt concentration makes tidal freshwater swamps more bio-diverse than coastal saline wetlands. Rheinhardt (1992) found the "subcanopy of tidal freshwater swamps to be the most speciose among temperate swamp ecosystems thus far described in literature and may rank among the richest in temperate North America." The term "swamp" is synonymous with forested wetland (Mitsch and Gosselink 1993) and is defined as any wetland with a significant proportion of woody vegetation, high water tables, and saturated poorly aerated soils (Lugo *et al.* 1988). These types of wetlands are thought to be the most dynamic of all forested ecosystems (Mitsch and Gosselink 1993, Megonigal *et al.* 1997, Baker *et al.* 2001). They are considered to be important natural resources because they enhance water quality (via being a sediment and nutrient sink) and export organic debris to many aquatic food webs (Mitsch and Gosselink 1993). They also contribute to flood mitigation (Walbridge 1993).

1.3.1 Forested Wetland Creation

Several studies cited by (Minkin and Lad 2003) found that there was an extremely low success rate in creating or restoring forested wetlands. They also noted that the majority of impacts were to forested wetlands but only a small percentage of these systems were replaced. For example, in a study of sixty mitigation projects, while 72 hectares (ha) of forested wetland were impacted, only 10 ha of mitigation were proposed to be forested and of these 10 ha, only 7 actually became forested wetlands (Minkin and Lad 2003). Forested wetlands were less likely to be proposed as mitigation sites because of fear of failure and difficulty to establish relative to other wetland types.

Many factors can contribute to the failure of a created forested wetland. Most of these reasons are related to determining the correct elevation of the wetland. Some forested wetlands end up being too wet for the germination and establishment of tree species. On the other hand, once trees become large the increased transpiration alters hydrology making the site drier than originally planned. The survival of planted trees and the development of wetland vegetation in the understory are two important factors that depend on proper hydrology and largely determine the success of creating a forested wetland (Pennington and Walters 2006). The germination and establishment of trees which are adapted to wetland conditions may primarily depend on periodic water level fluctuations during the growing season (Middleton 2000, Pennington and Walters 2006).

1.3.2 Hydrology and Tides

In tidal wetlands there are three sources of water: precipitation, ground water and surface water. Surface water dominates water inputs and movement in tidal wetlands

(Rabenhorst 2001) and because of this, tidal events greatly influence the hydrology of these types of wetlands. Hydrology and C cycling are interconnected and affect other ecosystem functions such as nutrient cycling (Jones *et al.* 1996, Rodgers *et al.* 2004). For example, when hydroperiod (the period of time during which a wetland is covered by water) lengthens, decomposition rates are decreased because of the lack of oxygen and this in turn, decreases nutrient availability (Day *et al.* 1989). Fluctuations of the water table can also induce shifts between anoxic and oxidized conditions in the root zone, which increases root turnover (i.e., lower lifespan of individual roots) (Debell *et al.* 1984, Kozlowski 1984, Jones *et al.* 1996, Neatrour *et al.* 2005).

The duration of daily tidal cycles are approximately 12.5 hours, so there are two high and two low tides per day. The Chesapeake Bay usually has daily tidal ranges (difference between mean low and high tide) of < 1m (Rabenhorst 2001). The lunar cycle influences tides as well. When the sun, moon and earth are aligned, which occurs about 1.5 days after full and new moons, there are unusually high tides (spring tides). Seven days after spring tides, there are unusually low tides (neap tides).

The lunar tides are also characterized by yearly cycles, in which the relative magnitude of spring and neap tides increase or decrease depending on the season. The Chesapeake Bay tides start to decrease around October, reaching lowest in January and then start to increase, reaching maximum offset during the summer months before starting to decrease again in July. In addition to daily, monthly and yearly tidal influences, storm events, such as hurricanes, can also drastically influence hydrology and tide levels.

The pulsed hydrology in tidal wetlands increases their productivity (Conner and Day 1976, Mitsch and Ewel 1979, Brinson *et al.* 1981) mostly because of nutrient inputs associated with tides and oxygen inputs associated with moving water. For instance, Mitsch *et al*. (1979) showed that P inputs from precipitation were relatively minor when compared with inputs from nearby river flooding in an alluvial cypress swamp system. In addition to hydrology and nutrients, tidal events are also significant sources of seed and plant propagules. Neff and Baldwin (2005) studied seed inputs (water and wind) to a tidal freshwater marsh, and found that surface water was the primary source of seed dispersal to the site.

1.4 Microtopography in Created Wetlands

The term microtopography refers to local elevation changes that typically occur on the soil surface. Microtopography is a common feature in natural wetlands and forests (Bruland and Richardson 2005). The many sources of microtopography include: sediment accumulation, erosion, tree fall, root growth, litter-fall, animal activity (Bruland and Richardson 2004), windstorms (Londo 2001), and removal or deposit of materials during fluvial or tidal activity. The incorporation of microtopographic features into forested wetlands has been recommended because it creates heterogeneous soil and microclimate conditions for tree colonization and improves plant, and animal diversity (Titus 1990, Vivian-Smith 1997, Roy *et al.* 1999, Bruland and Richardson 2005, Pennington and Walters 2006). For example, Alsfeld (2007) found that wetlands containing microtopography had an increase in total and facultative plant richness, bird richness and relative abundance of the green frog (*Rana clamitans* Latreille).

Rheinhardt (1992) looked at twenty-three well developed tidal freshwater swamps in Virginia and found a positive relationship pit number and flood duration. Those swamps with a longer flooding duration were dominated by an ash and black gum community. This study also found that all the trees except for bald cypress were restricted to growing on mounds.

Mounding creates areas that are higher- usually above the saturated zone, whereas local depressions or wind throw pits have lower elevations that are usually constantly saturated. Mounds have greater nutrient availability elevations and also have higher soil and root temperatures during the growing season than lower elevations (Londo 2001). Root growth has been shown to be positively influenced by temperature (Burke and Raynal 1994). Mounds contribute aerated soil volume and can increase the rooting depth of seedlings (Londo 2001). Mounded sites also increase litter decomposition rates due to more optimal conditions for heterotrophic decomposers. These combined factors make mounds favored sites for tree establishment as forested wetlands often have lower productivity than upland areas. For example, Chimner and Hart (1996) found that white-cedar (*Thuja occidentalis* L.) regeneration in upper peninsula wetlands in Michigan were concentrated on mounds. Indeed, mounding has been used in silviculture since the 18^{th} century to prepare sites for reestablishing trees on wet sites (Londo 2001).

1.5 Redox Potential of Soil

Root growth has been shown to be primarily controlled by the redox status and moisture content of the soil (Steinke *et al.* 1996). Soil redox potential (Eh) is a measure of the tendency of the soil system to accept electrons (i.e.,, become chemically reduced = negative value) or to donate electrons (i.e.,, become oxidized = positive value). Well aerated soils have an Eh of +400 to +700 mV (Pezeshki 1991). Flooded soils can have an Eh as low as -300 mV (Pezeshki 1991). At a pH of 7, most upland or facultative plants exhibit reduced root elongation at an Eh below +350 mV Eh. At these lower redox potentials, oxygen is not present as a significant electron acceptor, and the microbial consortium sequentially utilizes alternative elements as terminal acceptors for energetic metabolism (Megonigal *et al.* 1996). For example, ferric ion is reduced to ferrous ion at +150 mV (at pH 7) and sulfate is reduced to sulfide at -150 mV (Pezeshki 1991).

1.6 Root Research in Wetlands and Saturated Soil

The study of roots growing in wetlands is still in its infancy due to the difficulty of collecting root data in saturated soils with traditional methods such as core sampling which is very labor intensive, time consuming and destructive (Steinke *et al.* 1996, Baker *et al.* 2001). However, not collecting below-ground root data significantly underestimates forest ecosystem activity (Vogt *et al.* 1986, Day and Megonigal 1993, Baker *et al.* 2001). Scientists studying the above-ground productivity of forested wetlands have mentioned that below-ground data would greatly increase their understanding (Baker *et al.* 2001).

Fine root dynamics are directly influenced by frequent hydrologic fluctuations such as in tidal wetlands (Baker *et al.* 2001), and relatively subtle changes in microenvironment (Vogt *et al.* 1993). Roots help prevent soil erosion (Steinke *et al.* 1996), and they contribute as much as 60% of annual soil organic matter (SOM) inputs (Day and Megonigal 1993, Rodgers *et al.* 2004). While fine roots (<1mm diameter) comprise less than 10% of total forest biomass, they can account for 50-75% or more of the total net primary productivity, which is the rate at which new biomass is accrued into the ecosystem (via carbohydrate accumulation in plant tissues) (Vogt *et al.* 1986, Megonigal and Day 1988, Powell and Day 1991, Jones *et al.* 1996). In addition, the proliferation of fine roots is critical to plant establishment and growth since they serve as the primary means for water and nutrient uptake (Farrish 1991).

Technological advances such as the MiniRhizotron system have made collecting data in wetland conditions more feasible. MiniRhizotrons allow direct observation of roots and makes it possible to study root growth, decay, and spatial distribution (Steinke *et al.* 1996). This device also allows data collection without destroying the live roots and with minimal disturbance to the wetland.

1.7 Plant Responses to Flooding

The timing, magnitude, and duration of a flooding event are all important in regulating primary productivity in wetland forests (Megonigal and Day 1992). For example, flooding during the growing season is much more harmful to plants than flooding during dormancy. Oxygen deficiency is the most important cause of flooding injury (Kozlowski 1984). Gengarelly and Lee (2005) found that flooding serves as a limiting factor to Atlantic white cedar (*Chamaecyparis thyoides* (L.) B.S.P.) seedling performance. Moving water contains more oxygen and therefore is less harmful to plants than stagnant water.

Hydrophytes are plants which are adapted to carrying on normal physiological processes during flooded, anoxic conditions. These plants usually have both physiological and morphological adaptations to help them thrive in saturated soil conditions which exclude other upland adapted plants. In the US Fish and Wildlife Service classification scheme (Natural Resources Conservation Service 2007), plants are classified into five categories based on the likelihood that they will occur in a wetland (Table 1).

When flooding occurs, redox potentials decrease in the saturated soil. The diffusion of oxygen through water- filled soil pores is about 10,000 times slower than through air- filled pores (Beauchamp and Hume 1997) and as oxygen is utilized in respiration, it is not replaced in saturated soil. At +350 mV Eh, most plants reduce root elongation due to absence of free oxygen in the soil (Pezeshki 1991). Water absorption is also reduced because elevated soil CO_2 concentrations cause increased resistance to water movement in the root cortex (Kozlowski 1984). Amounts of plant nutrients absorbed by the roots are generally lowered as well, due to the changes in nutrient availability and root decay. In addition, plant roots increase their anaerobic respiration (alcoholic fermentation). Translocation of carbohydrates is reduced in flooded plants due to the accumulation of toxic products of anaerobic respiration (Kozlowski 1984). These toxic products are usually released from aerial roots or hypertrophied lenticels and cease being produced when aerobic respiration restarts (Kozlowski 1984).

Above-ground, stomata usually close within a day or two of flooding (Kozlowski 1984) and due to this, photosynthesis rates decrease. In response to flooding, levels of plant hormones such as ethylene, auxins, and abscisic acid increase, whereas levels of gibberellins and cytokinins decrease (Kozlowski 1984). The formation of aerenchyma tissue is also induced by increased ethylene levels. Aerenchyma formation is an important morphological flooding adaptation because the amount of respiring tissue is reduced and, resistance to oxygen movement to the roots is lowered, all while maintaining sufficient structural support. Plant tolerance to low soil oxygen levels depends primarily on the capacity to transport oxygen from the leaves to the roots. With increased oxygen to the roots, aerobic respiration can start to occur. Oxygen diffused from the roots acts as a terminal electron acceptor when Fe (II) is oxidized by both autocatalytic and biotic mechanisms (Weiss *et al.* 2003). Diffusion of oxygen from the plant roots also allows bacteria present to oxidize compounds such as manganous ions which are present in flooded soils (Megonigal *et al.* 1996) and are toxic to roots. Some plant species can increase the redox potential in the rhizosphere by more than 200 mV (Pennington and Walters 2006) through evolution of oxygen from roots.

1.7.1 Root Growth

Plant root sensitivity to anoxic soil conditions is a commonly quoted explanation for shallow root systems in wetlands (Rodgers *et al.* 2004) and high water tables have been shown to reduce rooting depth. More specifically, many studies have shown that coarse and fine root production and biomass are highest in well aerated sites and lower in constantly inundated sites (Megonigal and Day 1992, Baker *et al.* 2001). Extended flooding may increase fine root turnover, while drier soil is thought to slow root turnover rates. Slower root turnover rates result in a higher fine root standing crop (i.e., more live roots) (Baker *et al.* 2001, Burke and Chambers 2003). On the other hand, Rodgers *et al.* (2003) states that although flooding decreases root elongation of individual roots, root density actually increases: therefore, below-ground production remains similar to periodically flooded sites. Jones *et al.* (1996), investigating microtopography and fertilizer effects on root growth in wetland forests, reported that roots responded to changes in elevation but not the addition of fertilizer. Fine root mass was positively correlated with elevation. In general, roots were least abundant in lower elevations called "hollows". The results of Roy *et al.* (1999) on microtopography indicated that at higher elevations (hummocks or hammocks), there was significantly lower soil water content, a deeper aerobic layer, and higher mean and maximum soil temperatures when compared to areas with lower topography.

1.7.2 Carbon Allocation

Carbon Allocation to below-ground biomass often constitutes 50% or more of annual net primary production (flux of atmospheric C to plant material) (Raich and Nadelhoffer 1989, Nadelhoffer and Raich 1992). It has been suggested that above-ground production and below-ground C allocation are strongly related in forests; i.e., one process controls the other OR both are controlled by the same factors (Powell and Day 1991). Studies of a variety of community types have demonstrated that in general, root biomass increases at approximately twice the rate of shoot biomass (Rodgers *et al.* 2004). Under conditions of low moisture, plants allocate more resources to the construction of fine roots (Powell and Day 1991). For example, on rarely flooded sites, below-ground allocation was found to be 3x greater than above-ground (Megonigal and Day 1988, Powell and Day 1991). In cases of flooding, less C was allocated to the roots, but below-ground production was significantly higher than above-ground production on rarely flooded sites (Megonigal and Day 1988). This differential C allocation may be an adaptation for survival since submergence of the entire top of a small tree will likely result in death.

1.7.3 Seasonal Influences on Roots

Root systems have been found to have distinct seasonal fluctuations in root numbers (Powell and Day 1991, Steinke *et al.* 1996) and extension. These fluctuations are influenced by temperature and seasonal source: sink alterations within the plant. For example, in temperate regions, fall leaf drop is preceded by resources being transferred to the roots (Steinke *et al.* 1996, Rodgers *et al.* 2004). Most root growth ceases during the winter (Powell and Day 1991) until late winter-early spring, when the highest rooting intensity and productivity of the season occur (Powell and Day 1991). During the reproductive phase in early summer, resources from roots are utilized for seed development (Steinke *et al.* 1996). Periodicity of root length density is not influenced by differing plant species populations (Rodgers *et al.* 2004). In Atlantic white cedar communities, as the plant community shifts from predominantly herbaceous to a woody plant dominance, it has been found that root growth becomes less seasonally dynamic (Rodgers *et al.* 2004).

1.7.4 Root Distribution

Regardless of the season, root distribution generally decreases with depth (Steinke *et al.* 1996). Roots tend to be concentrated in the surface soils (Powell and Day 1991, Baker *et al.* 2001) due to higher water and nutrient availability levels in the A horizon. In forested ecosystems, fine roots are most abundant in top 10-30 cm of soil (Burke and Raynal 1994, Mou *et al.* 1995, Hendrick and Pregitzer 1996, Rytter and Hansson 1996), and this has been reported to be particularly pronounced in forested wetlands (Lugo *et al.* 1988, Jones *et al.* 1996, Rodgers *et al.* 2004). Baker *et al.* (2001) found that 74% of the fine root mass was restricted to the upper 0-15 cm of the soil in a forested wetland. Powell and Day (1991) found that a significant portion of fine and small (<5 mm) root biomass occurred in the top 10 cm of the soil. These findings are probably also related to the depth of the zone of surface soil oxidation, because in the Jones *et al.* (1996) study, the greatest root density differences were found in the top 20 cm of soil, and this range was also mentioned to be the zone of rusting/oxidation on emplaced iron welding rods.

Resource acquisition from the soil can be maximized through increased root foraging efficiency (i.e., higher root length density), range (i.e., longer, but less branched root growth), or both (Rogers *et al.* 1994, Day *et al.* 1996). In dry months, Baker *et al.* (2001) found that fine roots grew deeper and concluded that this evidence supported the range foraging theory. Under saturated conditions, Neatrour *et al.* (2005) found that nutrient uptake and rooting patterns studied in a wetland at a detailed scale (within a 20 m x 20 m plot) were not positively correlated. The lack of soil oxygen, which is characteristic in wetlands, may have caused the roots to prefer more oxygen rich areas as opposed to nutrient rich places in the soil and this prevented efficient root foraging for nutrients in the wetlands.

1.7.5 Root Decomposition

Large amounts of roots die annually and contribute substrate for conversion into SOM in a similar magnitude as foliar litter (McClaugherty *et al.* 1984). The amount of organic accumulation in wetlands depends on the production of biomass (roots, leaves, etc.) created and the rate at which they decompose (Day and Megonigal 1993). Moisture has large impacts on root decomposition and nutrient cycling. Wetlands with longer periods of saturation have the slowest rates of root decomposition (Day and Megonigal 1993, Cole *et al.* 2001). The types of plants growing in the wetland can also have an influence on above-ground and below-ground decomposition (Atkinson and Cairns 2001). Saturation also influences C allocation- above vs. below-ground (as stated previously), and this determines the type of litter made which in turn also determines decomposition rates and nutrient availability (Aber *et al.* 1985, Powell and Day 1991).

1.8 Taxodium distichum (L.) L.C. Rich (bald cypress) Responses to Flooding

Megonigal and Day (1992) researched the responses of bald cypress saplings to two different flooding treatments- continuously (CF) and periodically flooded (PF). Initially, the trees in PF treatments produced highest root and shoot biomass. During the

2nd growing season, CF trees had increased biomass which coincided with the development of morphological adaptations to flooding. By the 3rd growing season there was no difference in total biomass between the two treatments, although there were differences between treatments with regards to root: shoot (R: S) ratios. PF trees allocated more C to the roots and developed deeper root systems (high R: S) while CF trees had higher above-ground production (low R: S). Megonigal and Day (1992) discussed that the decrease of R: S ratio in bald cypress was not due to dying/dead roots because few dead roots in the continuously flooded treatment were found. The decrease was actually due to increased C allocation to above-ground growth. As mentioned earlier, this is likely a survival mechanism for the tree because if the entire plant is submerged, the tree will die.

Anderson and Pezeshki (1999) found that many negative effects of flooding such as decreased biomass, stomatal conductance, photosynthesis, leaf number, and leaf area were not affected by periodic flooding treatments.

Bald cypress trees adapt to flooding in many ways such as:

- ceasing root elongation at lower redox potential than most plants
- developing aerenchyma
- quick recovery of stomatal conductance and photosynthesis
- decrease in root: shoot ratio
- developing adventitious/aerial roots
- changing its rooting morphology and developing “knees”
- developing buttressing of the lower trunk

While most plants reduce root elongation at +350 mV Eh, bald cypress trees do not cease root elongation until redox drops below +200 mV (Pezeshki 1991). Ethylene production from anaerobic respiration stops root elongation and induces the formation of intercellular air spaces (aerenchyma tissue). Root porosity was found to increase in continuously flooded treatments (Kludze *et al.* 1994, Pezeshki and DeLaune 1996). Interestingly, Anderson and Pezeshki (1999) found that root porosity increased by 137% in intermittently flooded bald cypress. This very important tissue promotes oxygen transport to the roots and decreases the amount of respiring tissue while still maintaining structural support (Pezeshki 1991). The oxidation of the rhizosphere also makes it possible for the roots to perform aerobic respiration instead of anaerobic respiration. Bald cypress seedlings grown in constant flooding had initial reductions in stomatal conductance and net photosynthesis rates, but that these processes recovered within 2-3 weeks (Pezeshki 1991).

Bald cypress roots also respond to flooding by changing their direction of root growth. These roots can become diageotropic- which is when roots form at right angles to direction of gravitational force. They also become ageotropic- which is when roots form in the opposite direction of gravity. These roots become “cypress knees” which are thought to provide support to the tree and may also aid in oxygen exchange (Cronk and Fennessy 2001). Trees growing in constantly saturated soils tend to have even more of their roots distributed toward the top of the soil to facilitate gas exchange.

Trunk buttressing (swelling) is a flooding adaptation which occurs in many tropical/rainforest trees and also in bald cypress trees. A possible theory behind the cause of buttressing is that soil flooding results in a physiological girdle, and that this would inhibit the downward translocation of oxygen and also cause food and auxins to accumulate at the tree base, which stimulates the localized growth (Kramer and Koslowski 1960). The buttress begins at the soil surface and usually ends where the highest water levels reach. This expansion at the base of the tree and is thought to provide stability, support and strength to trees to prevent uprooting or windthrow from shallow rooting and/or poor anchorage. Indeed the definition of the word “buttress” means to support, reinforce, structure, and strengthen (Dictionary.com 2007). Another theory is that buttressing could produce a “snowshoe effect”, dispersing the trees compressive force over a greater surface area, which would reduce trunk settling/sinking down into the soil and consequent root damage (Smith 1972). Buttressing was found to be a reliable indicator of inundation in research where wetland boundaries are encircled by abrupt and obvious changes in ecosystem structure (Segal *et al.* 1987). The Corps of Engineers Wetlands Delineation Manual (Environmental Laboratory 1987) consider trunk buttressing a supporting indicator of the presence of hydrophytic vegetation.

1.9 Soil Amendments in Created Wetlands

Without suitable soil conditions, created wetlands may never be able to become functionally equivalent to natural wetlands (Bruland and Richardson 2005). Many studies comparing created wetlands with natural wetlands have found that created wetlands often have low soil organic matter (SOM), the organic fraction of the soil excluding undecayed plant and animal residues, relative to the levels found in natural wetlands (Langis *et al.* 1991, Shaffer and Ernst 1999, Stolt *et al.* 2000, Cole *et al.* 2001, Campbell *et al.* 2002, Bergschneider 2005, Daniels *et al.* 2005, Fajardo 2006). Soil organic matter is provided in the form of soil amendments such as mulch, compost, OM rich topsoil, wood chips, hay, and other high C materials which provide materials and energy necessary to sustain metabolism within the ecosystem. Additionally, SOM improves water retention of the soil, speeds the development of hydric soils, is a nutrient source, and can be a source of seed and plant propagules, and provide beneficial soil organisms. Organic material is a major N storage pool (Woodwell *et al.* 1979). SOM also affects N supplies since it is an energy source for nitrogen fixing bacteria (Gibson *et al.* 1994). Marshes with deeper organic material layers recycle N more effectively than marshes with shallow layers (Morris and Bowden 1986).

Nutrient status limits ecosystem development and created wetlands may not achieve functional equivalency to natural wetlands if essential nutrients, particularly N and P, are not available or are at low levels (Craft *et al.* 1991, Langis *et al.* 1991). As many as 15-30+ years in order for a created wetland to develop N and organic C pools equal to that of natural wetlands (Craft *et al.* 1988).

1.10 Soil Amendment Studies

Stauffer and Brooks (1997) demonstrated that the addition of organic material to soils in created palustrine wetland in Pennsylvania, greatly assisted the development of vegetation. Soil amendments also aid in the development of hydric soils, which is one of the requirements in order to establish that a created wetland is becoming a functional wetland. Vepraskas and Sprecher (1997) reported that created wetlands can develop hydric soil indicators within five years under proper conditions.

In a short-term study, Gibson *et al.* (1994) found that addition of amendments such as inorganic N, alfalfa (with and without N), and straw (with and without N) to a constructed intertidal marsh did not increase SOM. Nevertheless, other studies have shown that addition of organic amendments does positively affect the development of soil related functions in created wetlands. For example, Anderson and Cowell (2004) found that addition of wetland topsoil to created wetlands increased SOM and increased concentrations of the secondary macro-elements (Mg, Ca, and K). Species diversity and richness was more stable through the seasons in the mulched wetland. Even 5-10 years after construction, the initial mulching was influencing ecosystem development. Bruland and Richardson (2004) found that adding topsoil to created wetlands increased SOM, soil moisture, water holding capacity and P-sorption index. The P-sorption index measures the soils ability to absorb P. Increased indicates an increasing degree of P saturation.

Bergschneider (2005) found that total biomass and *Betula nigra* L. growth increased with compost amendment loading rate to a constructed non-tidal wetland soil, but that loading rates exceeding 112 Mg/ha led to higher surface elevations and redox levels in the initial growing season. This soil organic amendment research also found significant effects of compost loading rates on soil bulk density, redox potential, feature formation and soil moisture content. Surface bulk density decreased with loading rates of 224 Mg/ha and then reached equilibrium. Redox potential decreased and the presence of redox features increased as the compost loading rate was increased to 112 Mg/ha. Soil moisture content in the drier wetland tested increased up to a loading rate of 112 Mg/ha.

In addition to direct organic C effects, species richness has been found to be related to N: P ratios. Gusewell *et al.* (2005) found that sites with high N: P ratios were more species-poor than those with low N: P ratios. In addition, a smaller species pool size was found at sites with high N: P ratios, which suggests that fewer species are adapted to P-limited conditions than to N-limited conditions.

In a comparative study by Alsfeld (2007), wetlands that had been amended with coarse woody debris produced more insect biomass and higher total and obligate wetland plant richness. Interestingly, wetlands that had been amended with organic matter did not have a greater percent of SOM, but increased insect richness and diversity, and increased macroinvertebrate biomass were found.

Heaven *et al.* (2003) attributed topsoil/seed bank transfer as the primary reason for a created wetland success via insuring the appropriate wetland vegetation. Wetland enclosure experiments by McKinstry and Anderson (2003) demonstrated that the addition of topsoil to bentonite mine wetlands can increase plant numbers and growth weights by >50% for most of the species tested which included: Marsh smartweed (*Polygonum amphibium* L.), Hardstem bulrush (*Scirpus acutus* Muhl.), Softstem bulrush (*Scirpus validus* Vahl.), Alkali bulrush (*Scirpus maritimus* L.), and Spikerush (*Eleocharis palustris* L.).

1.10.1 Carbon Allocation

At the whole ecosystem scale, the availability of nutrients directly influences the proportion of above-ground vs. below-ground plant biomass. In several studies, a negative relationship was found between soil nutrients/fertility and root biomass (Aber *et* *al.* 1985, Gower and Vitousek 1989). This is because in infertile ecosystems, trees need to appropriate more C resources to root growth because more roots are needed to obtain necessary nutrients. Trees appropriate less C to roots in fertile ecosystems because not as many roots are necessary for adequate nutrient uptake (Nadelhoffer 2000). It is possible then that fine root turnover in fertile ecosystems may lead to higher root production even though fine root biomass decreases with increasing fertility (Nadelhoffer and Raich 1992, Hendricks *et al.* 1993, Nadelhoffer 2000, Neatrour *et al.* 2005).

1.11 Summary

Created wetlands often fail to re-establish the valuable functions of the wetlands that they are supposed to replace. Therefore, improvements of wetland creation practices are important in order for society to successfully mitigate the inevitable loss of natural wetlands and their functions. The additions of microtopography and soil amendments have been shown to improve certain aspects of wetland functions. Microtopography (pits and mounds) provides the possibility of both saturated and unsaturated micro-sites over short distances within the wetland. There are various morphological and physiological plant responses to differential soil saturation. For instance, root growth often decreases in flooded soils while above-ground growth often increases due to changes in C allocation. The addition of soil amendments has been shown to encourage the development of hydric features in soils, increase soil moisture and water holding capacity, and increase species diversity, tree biomass and plant numbers.

Research Questions

Since addition of soil amendments and microtopography to created wetlands was thought to facilitate wetland function, this research focused on the effects of two types of surface soil amendments (topsoil and compost) and recreated microtopography on plant vegetation and the growth of bald cypress trees in experimental plots within the Weanack Wetland Mitigation Site (WWMS) near Richmond, Virginia. The specific questions this study was designed to answer include:

I. Will soil amendments affect species composition growing in the created wetland?
   a. Will there be a difference in dominant species present for each soil treatment?
   b. Which soil treatment will have the highest species diversity?
   c. Which soil treatment will have the highest proportion of hydrophytic/wetland plants?

II. Will soil amendments and microtopography affect above-ground growth of young bald cypress growing in the created wetland?
   a. If there are differences among soil treatments, which treatment(s) yield more above-ground growth?
   b. If there are differences among microtopography treatments, which treatment(s) yield more above-ground growth?

III. Will soil amendments and microtopography affect root growth in the created wetland?
   a. If there are differences among soil treatments, which treatment(s) yield more root growth?

b. If there are differences among microtopography treatments, which treatment(s) yield more root growth?

2 Description of the Experiment Site and Plots

2.1 Weanack Wetland Mitigation Site Description

This experimental area lies within the 2.74 ha Weanack Wetland Mitigation Site (WWMS) which is located adjacent to Shirley Plantation on the James River in Charles City County, VA (Figure 1, and Figure 2). This off-site compensation created wetland was initially constructed in October 2003 to compensate for wetland impacts resulting from the widening of State Route 199 around Williamsburg. It has three types of wetlands designated for replacement, namely emergent herbaceous, shrub-scrub, and forested (Figure 3), which are based upon elevation above mean low tide and the intended vegetation. The majority of the site compensates for forested wetland losses.

Figure 1. Aerial view of WWMS, taken 10/31/05 by Charles Carter, used with permission. The larger (blue) square represents the general location of the WWMS and the smaller (orange) square indicates the field experiment location within WWMS. Port Tobacco is behind the wetland.

Figure 2. Location of WWMS (red star) USGS 7.5 minute quadrangles, Hopewell, VA.

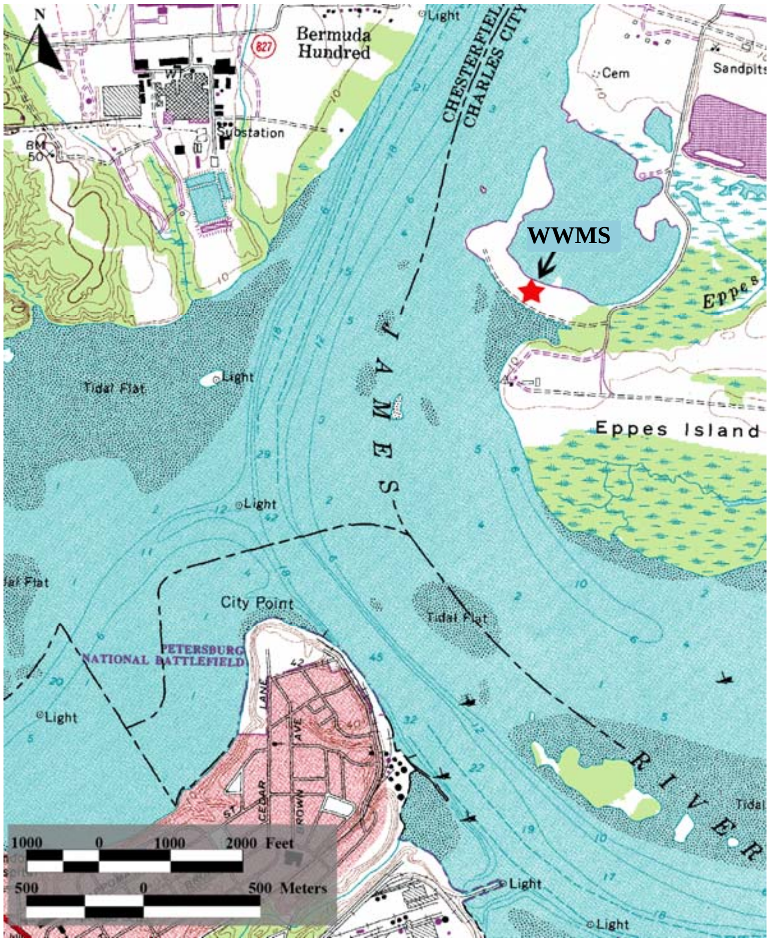
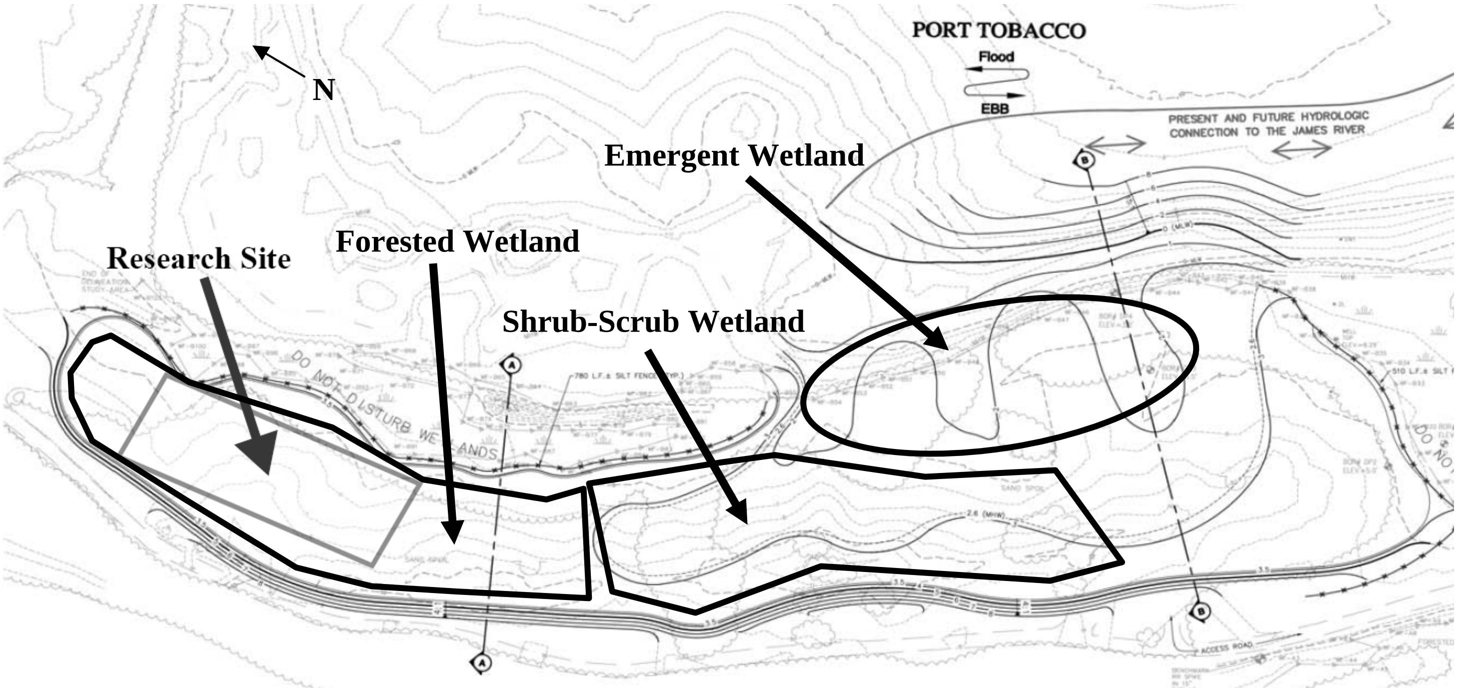


Figure 3. Location of the research site within WWMS (Vanasse Hangen Brustlin 2005), used with permission.

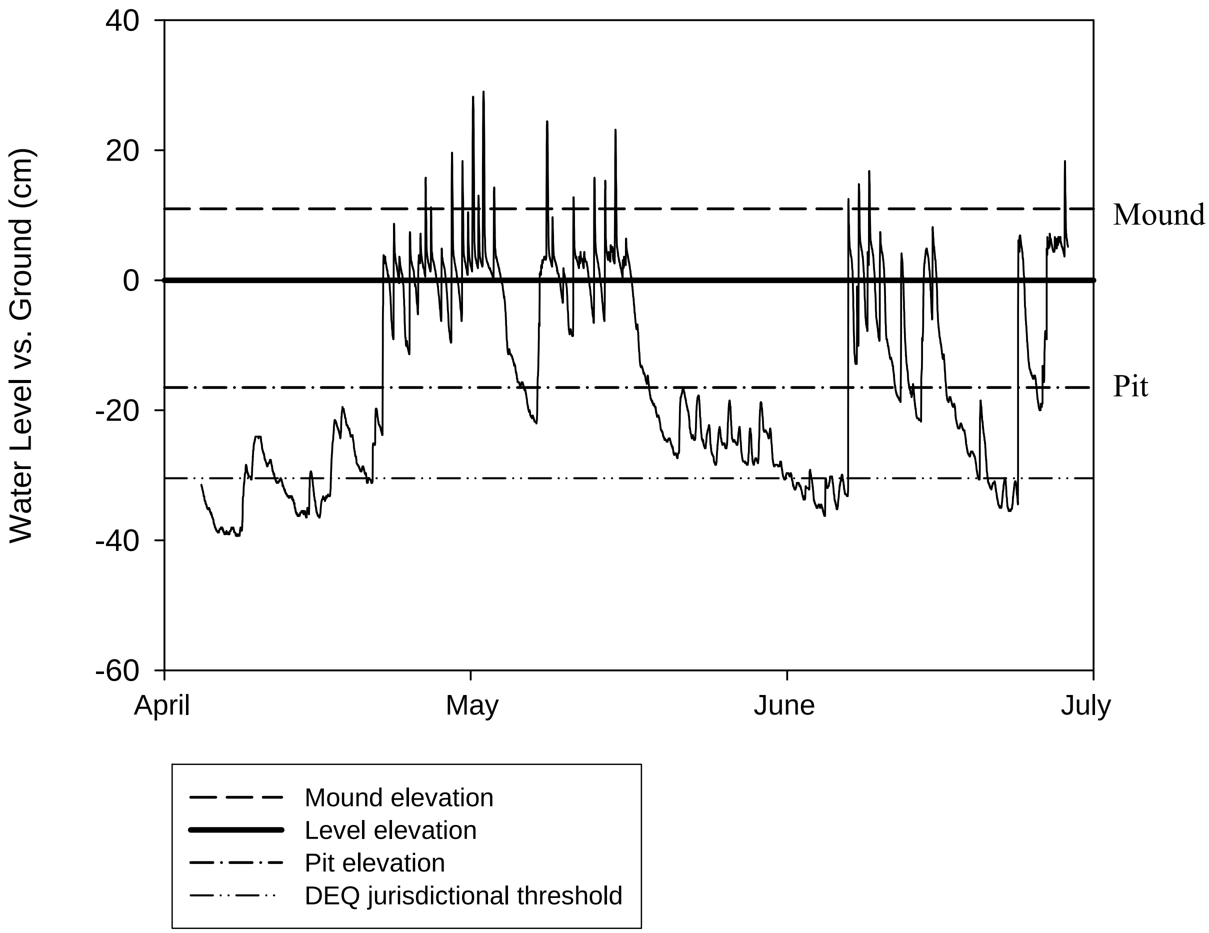


The material excavated from the site to achieve a suitable grade, just above the James River high tide, was predominantly (>95%) medium sand with a minor silt component. Total volume of material removed from the entire site was approximately 31,000 cubic meters. The sand was originally placed there by USCOE dredge discharge in 1950's-70's from maintenance cleaning of the adjacent James River shipping channel. Site design was based on features such as the topography and overall morphology of nearby natural wetlands, which are driven by tidal influxes from the James River into the Weanack port cove. The texture of the underlying soil materials is predominately sandy (Figure 4).

Figure 4. Stratified sandy dredge materials and surface soil at the WWMS site before excavation. Photographed by Lee Daniels, used with permission

According to the Year 2 Monitoring Report of the research site (Vanasse Hangen Brustlin 2005), the hydrology of the site met both the COE and DEQ criteria for jurisdictional wetland hydrology. Well readings also confirmed that the site was hydrologically connected to the tidal cycle of the James River and is indeed a tidal freshwater swamp (Figure 5).

Figure 5: Water level relative to ground surface (level), pit and mound elevation at the research site (well 7). Data were taken at 15 minute intervals from April 4, 2006 to June 28, 2006 (Vanasse Hangen Brustlin 2007), used with permission.



2.2 Experimental Plots

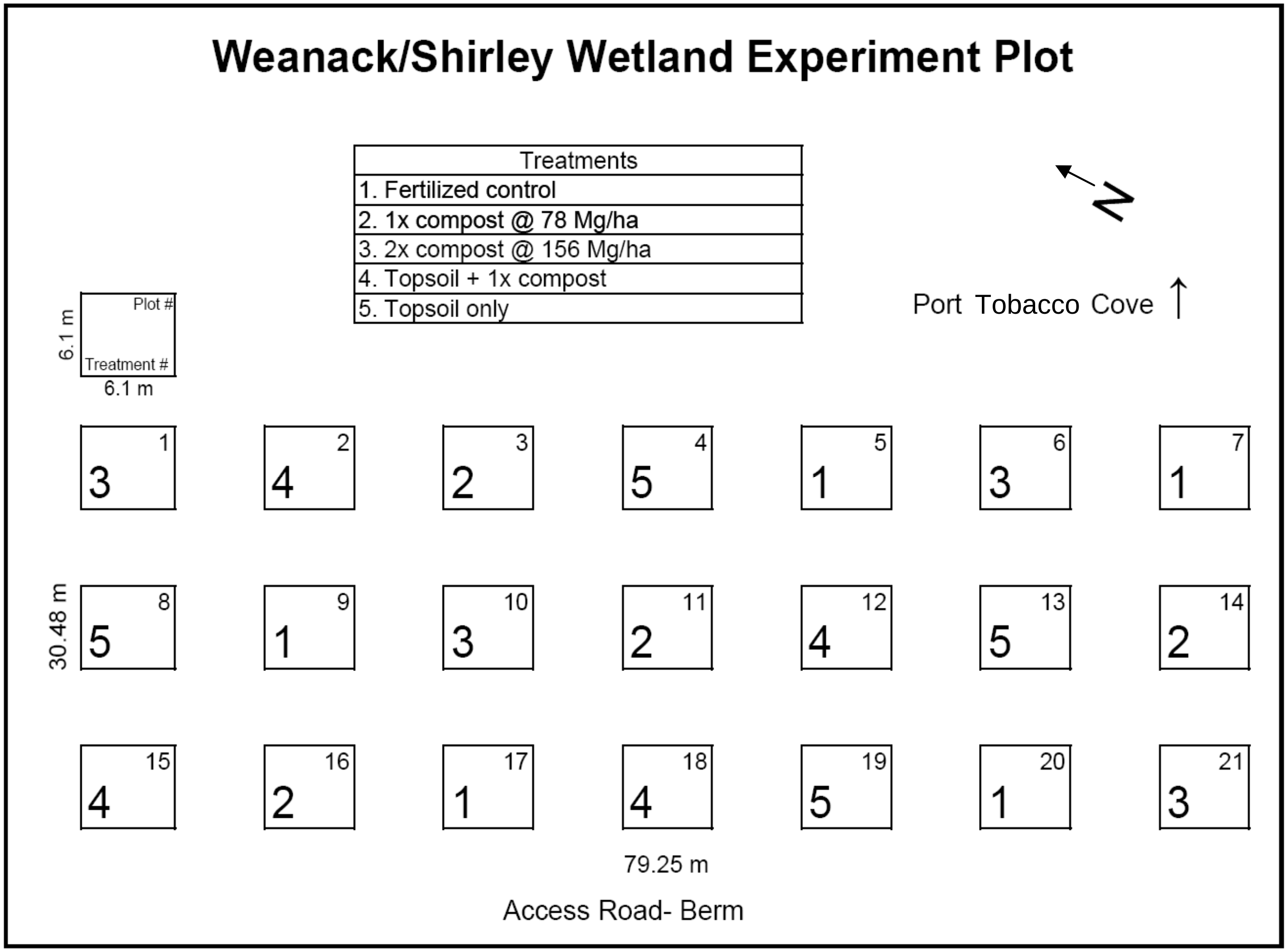
The experimental plots were located within the forested wetland section at WWMS with an elevation of 1.01-1.13 meters above mean low tide (Carter 2006) (Figure 6 and Figure 7). The original elevation was 2.13-2.74 meters above mean low tide (Carter 2006) (Figure 8). The experiment occupies 0.24 ha with overall dimensions of 30.5 m x 79.3 m containing 21 experimental plots that are 6.1 m x 6.1 m (Figure 9).

Figure 6. WWMS immediately after excavation October 7, 2003 facing northwest. Photograph by Lee Daniels, used with permission.

Figure 7. Picture of WWMS experiment plots taken facing northeast, December 2005. Photograph by Lee Daniels, used with permission.

Figure 8. WWMS before excavation facing northeast. Photograph by Lee Daniels, used with permission

Figure 9. Research site diagram showing treatments and plot locations. Figure by author.



2.3 *Materials and Methods*

2.3.1 Soil Treatments

Five soil reconstruction treatments were installed in a completely randomized design with four replications, with the exception of the control, which had five replications. A 6.1 m wide zone around each treatment plot was maintained as a buffer zone (Figure 9). During the installation of the treatments, equipment was kept within these buffer areas to minimize soil compaction of the plots. Topsoil from a local topsoil stockpile from sand and gravel mining was applied to the appropriate plots October 22, 2003 and yard waste compost (Grind-All LLC, Richmond, VA) was applied October 29, 2003. Plots not receiving compost were covered with plastic (Figure 10). Extra compost was collected from the plastic covers and used to extend double-compost treated plots approximately 1.25 m into adjacent buffer zones. All plots received 10-10-10 (N-P_2O_5-K_2O) fertilizer (LESCO Brand provided by Wetsel, Inc. in Harrisonburg, Virginia) at 280 kg/ha in October 2003. After soil treatments were applied to the plots, the entire experimental area was chisel plowed to 15 cm on October 30, 2003. Soil treatments are outlined below.

Soil Treatments:

1. Fertilized control (control): Existing sandy dredge spoil.
2. 1x yard waste compost (1x) at 78 wet Mg/ha (Table 2).
3. 2x yard waste compost (2x) at 156 wet Mg/ha.
4. 1x yard waste compost plus topsoil (1x+TS). Topsoil= 15 cm of local upland (Pamunkey) topsoil material added to the cut sandy surface. (Note: These plots

were undercut by 15 cm in to accommodate the additions without raising the overall final grade for this treatment and the following treatment- #5.)

5. Topsoil (TS) alone added over undercut sands per #4 above.

Figure 10. Site during the application of the soil amendments. The plastic was used to keep compost from being applied to non-compost plots and to capture compost for application to 2x compost plots. Photograph by Lee Daniels, used with permission.

Table 2. Results of analysis of yard waste compost amendments applied to plots, samples tested on October 23, 2003.

Parameter	WWMS Mulch
Solids (as is %)	50.4
Nitrogen (TKN %)	0.63
Phosphorus (%)	0.06
Potassium (%)	0.09
Sulfur (%)	0.10
Calcium (%)	1.04
Magnesium (%)	0.13
Sodium (mg/kg)	ND
Iron (mg/kg)	2980
Aluminum (mg/kg)	3860
Manganese (mg/kg)	660
Copper (mg/kg)	10
Zinc (mg/kg)	68
Ammonia-Nitrogen (mg/kg)	ND
NO_3-NO_2 Nitrogen (mg/kg)	46
Calcium Carbonate EQ (%)	1.5
EC (mS/cm;Wet)	0.34
TOC (%)	12.61
C:N	20.6

ND = Not determined.

Soil sampling performed in April 2004 indicated that treatments 1-3 had a USDA texture class of sand while treatments 4 and 5 (with topsoil) had a texture class of loam to silt loam (Appendix A). Soil analysis was performed on samples taken after soil treatments were applied to the plots and again in the spring of 2007 and (reported in Appendix B). Elevation measurements taken March 10, 2007 showed no significant elevation differences among soil treatments for average plot height.

2.3.2 Installation of Microtopography and Establishment of Vegetation

After initial installation of surface soil treatments in the fall of 2003, microtopography (pits and adjacent mounds to mimic physical effects of local tree wind throw) were hand-installed into each plot on March 8, 2004. Each pit was approximately 75 cm wide and 20 cm deep (Figure 11). The soil removed to make the pit was then used to make the adjacent mounds. Compost was added to the pit floors at the same rate as surface treatments; however, pits in topsoil-amended treatments were cut into the underlying sands (Figure 12). All of the mounds were approximately the same size, but lost approximately 25% of their initial elevation due to faunal digging in the first year. As of March 10, 2007, the mean pit elevation was 16.5 cm below level elevation (SD= 4.1); and the mean mound elevation was 11 cm above level elevation (SD= 3.2). See Figure 5. for microtopography elevation relative to hydrology for the 2007 growing season.

Container-grown bald cypress trees were planted into each pit and mound within each treatment plot at the same time as the other wetland trees were planted (April 23-26, 2004). Contract planters insured that at least one additional bald cypress tree was planted in each plot on neutral (level) elevation ground.

Figure 11. Plot with microtopography approximately two months after initial installation. Photograph by Lee Daniels, used with permission.

Figure 12. Site after the application of soil amendments and installation of microtopography in March of 2004. Photograph by Lee Daniels, used with permission.

The overall revegetation treatment (plant species and fertilizer) applied was consistent among all treatments. A seed mix containing 10-20% of each of the following species was applied to the wetland site at the rate of 84 kg/ha from May 10-14, 2004 (Carter 2006): *Polygonum persicaria* L., *Polygonum pensylvanicum* L., *Polygonum sagittatum* L., *Agrostis alba* L., *Lolium multiflorum* Lam., *Leersia oryzoides* L., *Carex crinita* Lam., and *Panicum rigidulum* Bosc ex Nees. All plots had 10-10-10 fertilizer applied at the rate of 280 kg/ha (as noted in the soil treatment section). To ensure seed-soil contact, a tractor pulled a chain-link fence scarification drag across the area after seeding and fertilization.

Second year tubeling trees (root cone: 5 cm diameter and 15 cm deep, trees 30-46 cm tall) were randomly intermixed at a density of 1086 trees/ha on April 23-26, 2004 (Carter 2006, McClintock 2006). Tree species include: *Quercus phellos* L. (willow oak), *Platanus occidentalis* L. (sycamore), *Fraxinus pennsylvanica* Marsh. (green ash), *Alnus serrulata* (Ait.) Willd. (tag alder), and *Taxodium distichum* (L.) L.C. Rich. (bald cypress). Each tree was planted with Osmocote 18-6-12, 7-gram slow-release tablets at the recommended rate (The Scotts Company, LLC, Marysville, OH). In particular, between two and five bald cypress trees were planted at each plot with one in each pit and mound. Trees were grown at Vanasse Hangen Brustlin's nursery in Chesapeake, VA. The seed for the trees came from either the Chickahominy River watershed north of Richmond or North Landing River Watershed in Virginia Beach. See Figure 13 for a view of the completed site.

Figure 13. Site in May of 2004 with recently planted vegetation. View is to the northeast. Photograph by Lee Daniels, used with permission.

3 Influences of Soil Amendments on Plant Population Characteristics at a Created Tidal Freshwater Swamp in Southeastern Virginia

3.1 Abstract

Addition of soil amendments to a created wetland may influence the timely development of valuable wetland functions. In this study, we measured the impact of adding soil amendments (control, 78 Mg/ha compost (1x), 156 Mg/ha compost (2x), 15 cm of topsoil (TS), and 1x+TS) on vascular plant composition. Plant data were collected in the fall of 2005 and spring and summer of 2006. Mean Importance values (IV), dominant species, similarity index, total species, species richness, evenness, diversity, and weighted averages (WA) were calculated for each soil treatment.

None of the treatments met U.S. Army Corps of Engineers criteria for hydrophytic vegetation which only considers dominant species. However, when using the same criteria with all species included, the control, 1x and 2x soil treatments had over 50% obligate wetland to facultative plant species, and therefore would have met jurisdictional vegetative criteria. When using WA's for vegetation success criteria, all the treatments except for the 1x+TS treatment would be considered hydrophytic. Due to these results, it is recommended that the current vegetative criteria for a jurisdictional determination in young wetlands be re-evaluated.

The addition of compost (1x or 2x) produced the highest proportion of obligate wetland species present (30%, and 27%, respectively). In contrast, addition of topsoil (1x+TS or TS) led to the lowest proportions of obligate wetland species (11%, and 13%, respectively) and the highest proportions of upland plants. Topsoil may have introduced more weed and upland seeds from its seed bank to the site. Thus, an existing seed bank appeared to be a disadvantage to the dominance of hydrophytic vegetation, species diversity and evenness. Due to these results, it is not recommended to add topsoil from upland locations during wetland creation, and donor soil from wetland environments is obviously a better option.

Overall, the control soil treatment provided the highest plant species diversity (3.5) and species richness (21) of all soil treatments. Treatments with topsoil had the lowest species evenness (0.77) and diversity (3.1). When considering these results, the addition of compost soil amendments during wetland creation is recommended to increase the amount of wetland species present at the site without compromising species diversity and evenness.

Key words: Tidal freshwater swamp, wetland creation, topsoil, compost, species diversity, hydrophytic vegetation.

3.2 Introduction

When creating wetlands, the equipment used to excavate soil to lower the elevation compacts the soil, removes topsoil, organic material, seed banks and natural microtopography. The removal of viable seeds from the native seed bank likely slows the recovery of wetland vegetation and desirable species may not reestablish before more aggressive early successional species move in (Brown and Bedford 1997). Many authors have questioned the notion that created wetlands will function similarly to the natural wetlands they supposedly replace (Langis *et al.* 1991, Reinartz and Warne 1993, Gibson *et al.* 1994, Shaffer and Ernst 1999, Zedler and Callaway 1999, Stolt *et al.* 2000, Zedler and Callaway 2000, Cole *et al.* 2001, Stolt *et al.* 2001, Zedler *et al.* 2001, Zedler and

Kercher 2005). Measures of wetland function in relation to plant growth includes the status of: invasive species, plant canopy, biodiversity, patterns of succession, seedling competition, and avoidance of soil erosion (Teal and Peterson 2005).

Tidal freshwater swamps are wetlands that are affected by the tidal fluctuations, but are inland enough so that water is low in salinity (< 0.5 ppt). This relatively low salt concentration makes tidal freshwater swamps more bio-diverse than coastal saline wetlands. Rheinhardt (1992) found the "subcanopy of tidal freshwater swamps to be the most speciose among temperate swamp ecosystems thus far described in literature and may rank among the richest in temperate North America." The term "swamp" is synonymous with forested wetland (Mitsch and Gosselink 1993) and is defined as any wetland with a significant proportion of woody vegetation, high water tables, and saturated, poorly aerated soils (Lugo *et al.* 1988). Tidal events greatly influence the hydrology of these types of wetlands. In addition to hydrology and nutrients, tidal events are also significant sources of seed and plant propagules. Neff and Baldwin (2005) studied seed inputs (water and wind) to a tidal freshwater marsh water was the primary source of seed dispersal to the site. The survival of planted trees and the development of wetland vegetation in the understory are two important factors when determining the success of creating a forested wetland (Pennington and Walters 2006). Heaven *et al.* (2003) attributed topsoil/seed bank transfer as the primary reason for a created wetlands success in having appropriate wetland vegetation.

Many studies comparing created wetlands with natural wetlands have found that created wetlands often have low soil organic matter (SOM) relative to the levels found in natural wetlands (Langis *et al.* 1991, Shaffer and Ernst 1999, Stolt *et al.* 2000, Cole *et al.*

2001, Campbell *et al.* 2002, Bergschneider 2005, Daniels *et al.* 2005, Fajardo 2006). Soil organic matter provided in the form of soil amendments such as mulch, compost, topsoil, hay and other high C materials which provide materials and energy necessary to sustain metabolism within the ecosystem. Additionally, SOM improves water retention of the soil, speeds the development of hydric soils, is a nutrient source, and can be a source of seed and plant propagules, and provide beneficial soil organisms. Bruland and Richardson (2004) found that adding topsoil to created wetlands increased SOM, soil moisture, water holding capacity and P-sorption index. Anderson and Cowell (2004) found that addition of wetland topsoil to created wetlands did increase SOM and also increased concentrations of the secondary macro-elements (Mg, Ca, and K). Species diversity and richness was more stable through the seasons in the mulched wetland. Even 5-10 years after construction, the initial mulching was influencing ecosystem development. Stauffer and Brooks (1997) also demonstrated that the addition of organic material to soils in a created palustrine wetland in Pennsylvania, greatly assisted the development of vegetation.

In past studies, Balcombe *et al.* (2005) found that species richness, evenness, and diversity were actually greater in mitigation wetlands but that there were major differences in species composition. Mitigation sites had more pioneer species, non-native dominants and species with lower conservation quality. When comparing vegetation growing in a created wetland to a natural wetland, Heaven *et al.* (2003) found that 65% of the plants were obligate wetland species in the natural wetland while the created wetland comprised 34% obligate species. More upland species were found in the created wetland as well.

The purpose of this study was to determine how the addition of soil amendments during wetland creation influences species composition in terms of diversity, evenness, and dominant species after several growing seasons.

3.3 Materials and Methods

3.3.1 Site Description and Application of Treatments

See chapter 2 for a complete site and treatment description. Note that the microtopography treatments were not included in this study.

Elevation measurements taken March 10, 2007 showed no significant elevation differences among soil treatments. Invasive species such as purple loosestrife (*Lythrum salicaria* L.) and cattail (*Typha latifolia* L.) were controlled by periodic hand pulling.

3.3.2 Data Collected

Measurements of percent vegetative cover were collected from two randomly placed 1m x 1m quadrats in each plot on the following dates: September 10-11, 2005; May 18-19, 2006; and July 12-13, 2006. Percent cover per plot by plant species was visually estimated directly in the field as a value of 1 to 100% or trace (<1%) using a modified Braum-Blanquet cover scale (DeBerry and Perry 2004) where: 0 to1% = trace, 2 to 5% = 2.5%, 6 to 25% = 15%, 65 to 50% = 37.5%, 51 to 75% = 62.5%, 76 to 95% = 85%, and 96 to 100% = 97.5%. Plant taxonomy, nomenclature, wetland indicator status (described in the next section), and nativity to the US followed the Natural Resources Conservation Service Plants Database (2007).

3.3.3 Formulae Used

Relative dominance was determined by dividing percent coverage of an individual species by the total percent coverage of all species (Smith 2001). Relative frequency is determined by dividing the frequency (presence or absence) of an individual species by the frequency value of all species.

Importance values (IV) were calculated using the sum of relative dominance and relative frequency for each species. Subsequently, species were ranked in order by decreasing IV; the first 50% were determined to be the dominant species.

The Sørenson Similarity Index (SI) (Maguerran 1988) was used to find differences/similarity in dominant species composition between different soil treatments. The equation for this index is:

Equation 1. Sørenson Similarity Index (SI).

$$SI=2c/ (a+b)$$

Where c is the number of species the two treatments have in common, 'a' is the total numbers of species in the first treatment, and b is the total number of species in the second treatment. Values above 0.5 indicate that the two treatments were similar in composition and values below 0.5 indicate that the two treatments are dissimilar (Mueller-Dombois and Ellenburg 1974).

In the US Fish and Wildlife Service classification system (Natural Resources Conservation Service 2007) plants are classified into five categories based on the likelihood that they will occur in a wetland. These five classes are: 1) Obligate wetland (OBL) species, which occur more than 99% of the time in wetlands; 2) Facultative wetland (FACW) species, which occur in wetlands 67-99% of time; 3) Facultative (FAC) species, which tolerate both wet and dry conditions and are found in wetlands 34-67% of time; 4) Facultative upland (FACU) plants are found in wetlands between 1 and 34% of time; 5) Obligate upland (UPL) plants are almost never found in wetlands in the region in question (<1%) (Natural Resources Conservation Service 2007). Indicator values were assigned as follows: OBL=1, FACW+=1.67, FACW=2, FACW-=2.33, FAC+=2.67, FAC=3, FAC-=3.33, FACU+=3.67, FACU=4, FACU-=4.33, UPL=5 (See also Table 1).

Indicator values and IV were used to determine weighted wetness averages (WA) for each soil treatment. The WA is then the mean wetland indicator number for all data collection dates per soil treatment. Lower WA values mean the there were higher proportions of plants growing at the site with low wetland indicator status, which means that the species observed are more likely to be found in wetlands. Atkinson's (1991) study concluded that the WA provided more sensitive measure of revegetation success than the methods described in the '87 manual. WA was calculated by summing the products of the importance value of each species and that species' indicator value. This calculation is summarized in the following equation:

Equation 2. Weighted Wetness Averages Equation.

$$WA = (y1u1 + y2u2 + . . . + ymum) / \Sigma \, yi$$

Where y1, y2, . . . , ym are the relative IV values for each species in the soil treatment, and u1, u2, . . . , um is the species indicator value. They are divided by the total sum of the Importance Values of each species (yi) in the treatment.

Species richness was calculated both as the total number of species for each soil treatment (TSP) during the 3 data collection dates, and as a per plot average (SR).

The Shannon Index (H') is the most popular index used to determine species diversity. The higher H' is, the greater the chances are that the next species found will not be the same species as the previous one. Lower H' values mean that the likelihood is higher than the next species encountered will be the same as the previous one. The Shannon Index is calculated as shown below:

Equation 3. Shannon Index for species diversity (H').

$$H' = \sum_{i=1}^{s} (p_i)(\ln p_i)$$

Where s is the number of species, ln is the natural log, p_i is the proportion of individuals of the total sample belonging to the i-th species. (Smith 2001).

Species evenness (J') is a diversity index that measures how equal species populations are in terms of numerical value (Smith 2001). The resulting number is between 0 and 1 and the species diversity index is used in the equation to determine evenness.

Equation 4. Species Evenness (J').

$$J' = H'/\ln s$$

H' is the species diversity index and s is the total number of species in a given treatment. The more evenly distributed (lower variation) the species populations are, the closer J' is to 1. This would indicate that there are higher numbers of dominant species (rather than just 1 or 2 dominant species) (DeBerry 2006). For example, if there were 2 dominant species and the rest of the populations were at low proportions, J' would be low (< 0.5) whereas if there were 8 dominant species and the rest of the species populations were similar, J' would be very close to one.

Weighted wetness average (WA) and Species Richness per plot (SR) were tested for normality using the goodness of fit procedure in JMP version 6 (2006). No treatment distributions were found to be non-normal and 1-way ANOVA (F-test) was performed. If the overall F-test was found to be significant ($p < 0.05$), the Student's t- test was used for pairwise mean separations ($\alpha = 0.075$).

3.4 Results and Discussion

A total of 38 families and 97 species were found in total over the sampling period between September 2005 and July 2006 (Table 3). There were 11 species of *Carex* identified at the site. Some *Carex* could not be identified due to lack of flowers and seeds and were denoted as *Carex* spp. Two *Juncus* species were identified at the study sites. Some *Juncus* plants could not be identified and are denoted as *Juncus* spp. There were 65 perennial, 17 annual, 11 annual/perennial, and 3 annual/biennual plant species (Table 3). *Agalinis purpurea* (L.) Pennell was dominant in four soil treatments: the control, 1x, 2x and TS soil treatments (13.41, 9.99, 4.93, and 6.69 IV respectively). *Lespedeza cuneata* (Dum.-Cours.) G. Don was dominant in the control, 1x, TS and 1x+TS soil treatments (7.07, 5.54, 7.22, and 7.82 IV, respectively). *Trifolium hybridum* L. was found to be a dominant species in 1x, 2x, TS and 1x+TS soil treatments (5.23, 10.52, 8.37, and 7.79 IV, respectively). For the control and 1x soil treatment, *A. purpurea* had the highest IV's, at

13.41 and 9.99 respectively. The 2x soil treatment produced *T. hybridum* for the highest IV at 10.52. Both treatments containing topsoil, TS and 1x+TS, supported *Juncus tenius* as the plant species with the highest IV, 13.21 and 12.72, respectively (Table 4-8).

Table 3. Plant species occurring at the WWMS site and average Importance Values (IV) for three data collection dates. Plant names are followed by wetland indicator status (Indicator), plant life strategy (Duration), and native status (US Nativity). Nomenclature, wetland indicator status, plant life strategy and native status all follow the NRCS PLANTS Database (2007). IV is divided into each soil treatment; control= no amendment, 1x= compost at 78 mg/ha, 2x= compost at 156 mg/ha, TS= 15 cm topsoil, and 1x+TS.

Species	Indicator	Duration	US nativity	Control	1x	2x	TS	1x+TS
Aceraceae								
Acer rubrum L.	FAC	perennial	native	1.47	1.53	0.82	0.75	1.14
Amarthanthaceae								
Amaranthus cannabinus (L.) Sauer	OBL	perennial	native	0.10		0.12	0.13	0.15
Apiaceae								
Ptilimnium capillaceum (Michx.) Raf.	OBL	annual	native	1.74	1.50	1.43	0.61	0.66
Asclepiadaceae								
Asclepias incarnata L.	OBL	perennial	native			0.16		
Asteraceae								
Ageratina altissima var. *altissima* (L.) King & H.E. Robins.	FACU-	perennial	native	0.32	1.44	0.32	0.27	0.06
Ambrosia artemisiifolia L.	FACU	annual	native	1.55	3.38	2.23	1.32	2.01
Bidens laevis (L.) B.S.P.	OBL	ann/pere	native	0.66			0.14	
Eclipta prostrata (L.) L	FAC	ann/pere	native	2.49	1.85	2.63	0.81	0.27
Erigeron annuus (L.) Pers.	FACU	annual	native			0.04		

Table 3. Continued

Species	Indicator	Duration	US nativity	Control	1x	2x	TS	1x+TS
Asteraceae								
Eupatorium capillifolium (Lam.) Small	FACU-	perennial	native	6.46	2.81	1.92	1.19	0.45
Euthamia graminifolia (L.) Nutt.	FAC	perennial	native	0.47				
Helenium autumnale L.	FACW+	perennial	native	1.05	3.37	3.23	4.86	6.48
Lactuca canadensis L.	FACU-	ann/bie	native					0.13
Mikania scandens (L.) Willd.	FACW+	perennial	native	0.04	0.25	0.32	0.05	0.15
Silphium perfoliatum L. var. *connatum* (L.) Cronq.	FACU	perennial	native	0.51				
Solidago altissima L.	FACU-	perennial	native	2.27	3.42	0.52	2.91	5.00
Solidago gigantea Ait.	FACW	perennial	native			0.59		
Symphyotrichum lanceolatum (Willd.) Nesom	FAC	perennial	native	2.40	2.65	4.40	6.70	4.35
Xanthium strumarium var. *canadense* L. (P. Mill.) Torr. & Gray	FAC	annual	native			0.06	0.00	0.00
Balsaminaceae								
Impatiens capensis Meerb.	FACW	annual	native			0.04	0.13	0.05
Bignoniaceae								
Campsis radicans (L.) Seem. ex Bureau	FAC	perennial	native	0.08				0.16

Table 3. Continued

Species	Indicator	Duration	US nativity	Control	1x	2x	TS	1x+TS
Buddlejaceae								
Polypremum procumbens L.	UPL	ann/pere	native	0.08			0.11	
Chenopodiaceae								
Chenopodium album L.	FACU+	annual	nat/int					0.06
Clusiaceae								
Hypericum mutilum L.	FACW	ann/pere	native	0.10	0.14			
Commelinaceae								
Murdannia keisak (Hassk.) Hand.-Maz.	OBL	perennial	introduced	0.80	0.12	1.91	0.05	0.06
Convolvulaceae								
Ipomoea pandurata (L.) G.F.W. Mey.	FACU	perennial	native	0.04			0.11	0.22
Cupressaceae								
Taxodium distichum (L.) L.C. Rich.	OBL	perennial	native	0.04				0.11
Cyperaceae								
Bulbostylis warei (Torr.) C.B. Clarke	FACU	perennial	native		0.64			
Carex spp. L.	OBL	perennial	native	3.94	4.41	4.81	0.85	2.81
Carex alata Torr.	OBL	perennial	native	0.26	0.00	0.59	0.13	0.00
Carex annectens (Bickn.) Bickn.	FACW	perennial	native	0.57	1.61	1.55	2.31	1.99

Table 3. Continued

Species	Indicator	Duration	US nativity	Control	1x	2x	TS	1x+TS
Cyperaceae								
Carex crinita Lam.	OBL	perennial	native	3.23	8.64	3.40	3.22	1.56
Carex frankii Kunth	OBL	perennial	native	2.38	5.13	3.90	0.83	4.58
Carex lupuliformis Sartwell ex Dewey	FACW	perennial	native	0.47	0.59	0.10	0.61	
Carex lupulina Muhl.	OBL	perennial	native		0.14			
Carex lurida Wahlenb.	OBL	perennial	native		0.80		0.13	
Carex normalis Mackenzie	FACU	perennial	native	0.08				
Carex scoparia Schkuhr ex Willd.	FACW	perennial	native	0.10	0.80	0.91		0.63
Carex tribuloides Wahlenb.	FACW+	perennial	native		1.29			0.62
Carex vulpinoidea Michx.	OBL	perennial	native		0.80	0.10	0.32	0.73
Cyperus spp. L.	FACW	n/a	n/a	1.33	1.76	1.77	1.00	0.91
Cyperus filicinus Vahl	OBL	ann/pere	native	0.21	0.06		0.12	
Cyperus flavescens L.	OBL	annual	native	1.03	0.12	0.86	0.06	
Cyperus strigosus L.	FACW	perennial	native	0.80	0.97	0.06		0.23
Scirpus cyperinus (L.) Kunth	FACW+	perennial	native			0.74	0.14	0.11
Euphorbiaceae								
Acalypha rhomboidea Raf.	FACU-	annual	native	0.70	0.15	0.86	0.15	0.06

Table 3. Continued

Species	Indicator	Duration	US nativity	Control	1x	2x	TS	1x+TS
Fabaceae								
Apios americana Medik.	FACW	perennial	native				0.61	
Kummerowia striata (Thunb.) Schindl.	FACU	annual	introduced	1.60	2.07	1.63	0.11	0.21
Lathyrus latifolius L.	UPL	perennial	introduced		0.14		4.47	2.92
Lespedeza cuneata (Dum.-Cours.) G. Don	UPL	perennial	introduced	7.07	5.54	2.64	7.22	7.82
Lespedeza virginica (L.) Britt.	UPL	perennial	native	3.30	4.53	3.85	2.93	2.92
Strophostyles helvula (L.) Elliott	FACU-	annual	native	4.23	2.85	5.67	3.83	9.40
Trifolium hybridum L.	FAC-	ann/pere	introduced	2.64	5.23	10.52	8.37	7.79
Fagaceae								
Quercus phellos L.	FACW+	perennial	native	0.04	0.00			0.06
Geraniaceae								
Geranium dissectum L.	UPL	ann/bie	introduced	0.00	0.19	0.13		
Iridaceae								
Sisyrinchium angustifolium P. Mill.	FACW-	perennial	native				2.51	1.63
Juncaceae								
Juncus spp. L.	FACW	perennial	native					0.78
Juncus effusus L.	FACW+	perennial	native	0.79	2.39	3.58	11.20	7.65

Table 3. Continued

Species	Indicator	Duration	US nativity	Control	1x	2x	TS	1x+TS
Juncaceae								
Juncus tenuis Willd.	FAC-	perennial	native	1.86	1.05	3.73	13.21	12.72
Lamiaceae								
Lycopus americanus Muhl. ex W. Bart.	OBL	perennial	native	0.03			0.74	0.22
Lythraceae								
Ammannia coccinea Rottb.	OBL	annual	native	0.66			0.06	
Lythrum salicaria L.	FACW+	perennial	introduced	0.10		0.13		
Rotala ramosior (L.) Koehne	OBL	annual	native	0.04		0.06		
Malvaceae								
Hibiscus moscheutos L.	OBL	ann/pere	native	0.69	0.74	0.04		
Kosteletzkya virginica (L.) K. Presl ex Gray	OBL	perennial	native			0.15		
Melastromataceae								
Rhexia virginica L.	OBL	perennial	native					0.06
Onagraceae								
Epilobium ciliatum ssp. *ciliatum* Raf.	FAC-	perennial	native	0.04				
Epilobium coloratum Biehler	OBL	perennial	native	0.18	0.14			
Jussiaea leptocarpa (Nutt.) Hara	OBL	ann/pere	native	0.00	0.06			

Table 3. Continued

Species	Indicator	Duration	US nativity	Control	1x	2x	TS	1x+TS
Onagraceae								
Ludwigia alternifolia L.	FACW+	perennial	native	0.66	0.06	0.06		
Oxalidaceae								
Oxalis dilleni Jacq.	UPL	perennial	native	0.03			0.05	0.09
Platanaceae								
Platanus occidentalis L.	FACW-	perennial	native	0.10				
Poaceae								
Agrostis gigantea Roth.	FACU	perennial	introduced	5.04	4.20	5.58	2.76	2.64
Andropogon virginicus L.	FACU	perennial	native	2.07	0.10	1.17		0.11
Arthraxon hispidus (Thunb.) Makino	FACU+	annual	introduced		0.10			
Dichanthelium boscii (Poir.) Gould & C.A. Clark	UPL	perennial	native	1.85	0.70	1.19		0.11
Dichanthelium scoparium (Lam.) Gould	FACW	perennial	native	0.65	0.06			
Echinochloa crus-galli L. Beauv.	FACU	annual	introduced		0.06		0.14	
Elymus virginicus L.	FACW-	perennial	native				0.05	
Leersia oryzoides (L.) Sw.	OBL	perennial	native	1.37	3.04	6.28	3.38	2.03

Table 3. Continued

Species	Indicator	Duration	US nativity	Control	1x	2x	TS	1x+TS
Poaceae								
Poa annua L.	FACU	annual	introduced	1.48	1.85	1.13	0.94	0.78
Sacciolepis striata (L.) Nash	OBL	perennial	native	0.19	0.15	0.15		
Sorghum halepense (L.) Pers.	FACU	perennial	introduced			0.59	0.23	0.06
Urochloa texana (Buckl.) R. Webster	UPL	annual	native			0.59		
Polygonaceae								
Polygonum hydropiperoides Michx.	OBL	perennial	native	0.93	0.96	0.12		
Polygonum sagittatum L.	OBL	ann/pere	native	1.79	3.38	2.98	0.10	0.09
Primulaceae								
Anagallis arvensis L.	UPL	ann/biennial	introduced				0.05	
Ranunculaceae								
Ranunculus sardous Crantz	UPL	ann/bie/pere	introduced	0.10				0.05
Rubiaceae								
Diodia virginiana L.	FACW	ann/pere	native	0.57				
Galium tinctorium (L.) Scop.	OBL	perennial	native			0.18		0.63
Salicaceae								
Populus deltoides Bartr. ex Marsh.	FAC	perennial	native	0.77	0.01	0.06		

Table 3. Continued

Species	Indicator	Duration	US nativity	Control	1x	2x	TS	1x+TS
Salicaceae								
Salix nigra Marsh.	FACW+	perennial	native	7.81	0.64	3.05	0.18	0.73
Scrophulariaceae								
Agalinis purpurea (L.) Pennell	FACW-	annual	native	13.41	9.99	4.93	6.69	3.40
Solanaceae								
Solanum carolinense L.	UPL	perennial	native				0.06	0.05
Typhaceae								
Typha latifolia L.	OBL	perennial	native	0.10		0.15	0.19	0.11
Ulmaceae								
Ulmus americana L.	FACW-	perennial	native	0.98	0.30	0.24	0.83	0.16
Verbenaceae								
Verbena urticifolia L.	FACU	perennial	native	0.03	0.10		0.11	0.05

OBL= Obligate Wetland species, FACW= Facultative Wetland species, FAC= facultative, FACU= Facultative Upland species, UPL= Upland species

Table 4. Dominant species for control soil treatment.

Species	Indicator	Duration	US nativity	IV
Agalinis purpurea (L.) Pennell	FACW-	annual	native	13.41
Salix nigra Marsh.	FACW+	perennial	native	7.81
Lespedeza cuneata (Dum.-Cours.) G. Don	UPL	perennial	introduced	7.07
Eupatorium capillifolium (Lam.) Small	FACU-	perennial	native	6.46
Agrostis gigantea Roth.	FACU	perennial	introduced	5.04
Strophostyles helvula (L.) Elliott	FACU-	annual	native	4.23
Carex spp. L.	OBL	perennial	native	3.94
Lespedeza virginica (L.) Britt.	UPL	perennial	native	3.30

OBL= Obligate Wetland species, FACW= Facultative Wetland species, FAC= facultative, FACU= Facultative Upland species, UPL= Upland species

Table 5. Dominant species for 1x (78 mg/ha compost) soil treatment.

Species	**Indicator**	**Duration**	**US nativity**	**IV**
Agalinis purpurea (L.) Pennell	FACW-	annual	native	9.99
Carex crinita Lam.	OBL	perennial	native	8.64
Lespedeza cuneata (Dum.-Cours.) G. Don	UPL	perennial	introduced	5.54
Trifolium hybridum L.	FAC-	ann/pere	introduced	5.23
Carex frankii Kunth	OBL	perennial	native	5.13
Lespedeza virginica (L.) Britt.	UPL	perennial	native	4.53
Carex spp. L.	OBL	perennial	native	4.41
Agrostis gigantea Roth.	FACU	perennial	introduced	4.20
Solidago altissima L.	FACU-	perennial	native	3.42

OBL= Obligate Wetland species, FACW= Facultative Wetland species, FAC= facultative, FACU= Facultative Upland species, UPL= Upland species

Table 6. Dominant species for 2x (156 mg/ha compost) soil treatment.

Species	**Indicator**	**Duration**	**US nativity**	**IV**
Trifolium hybridum L.	FAC-	ann/pere	introduced	10.52
Leersia oryzoides (L.) Sw.	OBL	perennial	native	6.28
Strophostyles helvula (L.) Elliott	FACU-	annual	native	5.67
Agrostis gigantea Roth.	FACU	perennial	introduced	5.58
Agalinis purpurea (L.) Pennell	FACW-	annual	native	4.93
Carex spp. L.	OBL	perennial	native	4.81
Symphyotrichum lanceolatum (Willd.) Nesom	FAC	perennial	native	4.40
Carex frankii Kunth	OBL	perennial	native	3.90
Lespedeza virginica (L.) Britt.	UPL	perennial	native	3.85
Juncus tenuis Willd.	FAC-	perennial	native	3.73

OBL= Obligate Wetland species, FACW= Facultative Wetland species, FAC= facultative, FACU= Facultative Upland species, UPL= Upland species

Table 7. Dominant species for TS (15 cm topsoil) soil treatment.

Species	**Indicator**	**Duration**	**US nativity**	**IV**
Juncus tenuis Willd.	FAC-	perennial	native	13.21
Juncus effusus L.	FACW+	perennial	native	11.20
Trifolium hybridum L.	FAC-	ann/pere	introduced	8.37
Lespedeza cuneata (Dum.-Cours.) G. Don	UPL	perennial	introduced	7.22
Symphyotrichum lanceolatum (Willd.) Nesom	FAC	perennial	native	6.70
Agalinis purpurea (L.) Pennell	FACW-	annual	native	6.69

OBL= Obligate Wetland species, FACW= Facultative Wetland species, FAC= facultative, FACU= Facultative Upland species, UPL= Upland species

Table 8. Dominant species from 1x+TS (compost at 78 mg/ha and 15 cm topsoil) soil treatment.

Species	**Indicator**	**Duration**	**US nativity**	**IV**
Juncus tenuis Willd.	FAC-	perennial	native	12.72
Strophostyles helvula (L.) Elliott	FACU-	annual	native	9.40
Lespedeza cuneata (Dum.-Cours.) G. Don	UPL	perennial	introduced	7.82
Trifolium hybridum L.	FAC-	ann/pere	introduced	7.79
Juncus effusus L.	FACW+	perennial	native	7.65
Helenium autumnale L.	FACW+	perennial	native	6.48

OBL= Obligate Wetland species, FACW= Facultative Wetland species, FAC= facultative, FACU= Facultative Upland species, UPL= Upland species

Agalinis purpurea (FACW-) is a native, annual plant which is a moderate (10-25% of diet) source of food for large mammals (Natural Resources Conservation Service 2007). This plant's primary seed dispersal is via wind and also by water and it is common to disturbed habitats. *Agalinis* is also considered a vascular semi-parasite and develops haustoria (specialized absorbing structure of a parasitic plant) when in the presence of *Lespedeza cuneata*. *Lespedeza cuneata* (UPL) is an introduced, perennial plant which is a low (5-10% of diet) source of food for large mammals, moderate cover for small mammals, and a moderate food and cover source for terrestrial birds (Natural Resources Conservation Service 2007). From personal observation, for an upland plant, it grows too well, for WWMS has proven hydrology and hydric soils. Early observations of the WWMS confirm that this weedy species originated from the plots containing topsoil (Daniels 2007). This plant is an upright species that forms deep taproots. The habit of *Lespedeza* shades out other plants and it is considered an aggressive species which may hinder the re-colonization of native species if not properly managed. *Lespedeza* tolerates infertile soils and a wide range of soil pH. The main seed dispersal methods for *Lespedeza* are anthropogenic in nature: haying activities and livestock. The seeds must be scarified in order to germinate and are capable of establishing and maintaining seed banks. *Lespedeza* detritus is slow to decompose and often accumulates thus hindering the germination of other plants. This plant also contains the allelopathic compounds catechin and epicatechin. *Trifolium hybridum* (FAC-) is an introduced plant which can be an annual or perennial. It is often seeded in pastures along with grass. Birds are often a vehicle of seed dispersal. The seed coat must be broken down or scarified for germination. Both *Trifolium* and *Lespedeza* are in the Fabaceae family and therefore provide sites for bacterial N-fixation. Sedges such as *Juncus* and *Carex* are often associated as dominant species in freshwater emergent wetlands (Cronk and Fennessy 2001). Both *Juncus* shoots and roots contain aerenchyma which allows them to cope with higher levels of flooding.

Of the original eight species in the seed mix, which were put onto all of the plots (discussed in 2.3.2), *Polygonum sagittatum*, *Leersia oryzoides*, and *Carex crinita* are the only ones which still remained on the site (Table 3). *Carex crinita* was a dominant species for the 1x treatment (8.64) and *Leersia oryzoides* was a dominant species on the 2x treatment (6.28 IV).

The Sørenson similarity index among soil treatments revealed that TS and 1x+TS; TS and 2x; 1x and 2x; 2x and control; and 1x and control soil treatments were all similar to one another (Table 9). In general, the compost treatment species composition was similar to the control treatment species composition and the topsoil treatment species compositions were similar to other topsoil treatments.

According to the 1987 manual (Environmental Laboratory 1987), in order to meet the hydrophytic vegetation criteria for jurisdiction, greater than 50% of the dominant species must have an indicator status of OBL, FACW, or FAC. None of the soil treatments met these criteria but, the 2x and TS soil treatments both had 50% OBL-FAC species (Table 4-8). When using the FAC neutral test (weighting abundance of OBL+ FACW vs. FACU+ UPL without including any FAC±) the 2x and TS soil treatments passed this test, (4:3 and 2:1 respectively) (Table 6, and Table 7). The other treatments did not meet the >50% criteria but the 1x and 1x+TS treatments both produced equal ratios (4:4 and 2:2, respectively) (Table 5, and Table 8). Therefore, in terms of improving chances of meeting USACE jurisdictional vegetation criteria, adding TS or 2x compost would enhance the presence of hydrophytic vegetation in the list of dominant species, but this still may not be enough to meet current wetland delineation criteria.

There was a marginal likelihood that soil treatment that affected WA ($p = 0.092$) (Table 10). In terms of WA values, those that are > 3 would be considered predominately upland plants while those < 3 would be predominately wetland plants. The 1x+TS soil treatment was the only one with a WA > 3 (3.06) and would be determined to be dominated by upland plants.

Soil treatment did have a significant effect on per plot species richness (SR) ($p = 0.014$) and mean separations revealed that the control soil treatment had a significantly higher SR (20.9 ± 0.84) than plots which were treated with amendments. The control soil treatment also had the highest total species (TSP) (68.00), and diversity (H') (3.69). Topsoil (TS) had the lowest TSP (56.00), SR (16.4 ± 0.98), and H' (3.11). The 1x soil treatment had the highest evenness (J') (0.85) and TS had the lowest (0.77) (Table 10).

In Anderson and Cowell's (2004) findings which compared mulched (transplant of wetland topsoil to created wetlands surface) to un-mulched created wetlands in Florida, they reported that in November, TSP and H' were higher for non mulched wetlands. In Anderson and Cowell's study, there was a drought from November to June and in the June, there was not a difference in TSP, but mulched wetlands had higher J' and H' because the un-mulched J' and H' had dropped. Mulching was thought to keep H' and J' more stable through the variability of the seasons. My data agree with this study's November data, where the control/non-mulched had the highest TSP and H' but further investigation would be needed to determine if this trend would continue even after periods of stress.

Table 9. Similarity Index matrix for dominant species among the soil treatments. Control= no amendment, 1x= compost at 78 mg/ha, 2x= compost at 156 mg/ha, TS= 15 cm topsoil, and 1x+TS.

Soil Treatment	**Control**	**1x**	**2x**	**TS**
1x	0.59			
2x	0.56	0.63		
TS	0.29	0.40	0.50	
1x+TS	0.29	0.27	0.38	0.67

Values > 0.5 are similar and values < 0.5 are dissimilar

Table 10. Mean values for each soil treatment for total species richness (TSP), species richness per plot (SR), Evenness (J'), Shannon Diversity Index (H'), and weighted wetness averages (WA) for all three data collection dates with wetland indicator. Control= no amendment, 1x= compost at 78 mg/ha, 2x= compost at 156 mg/ha, TS= 15 cm topsoil.

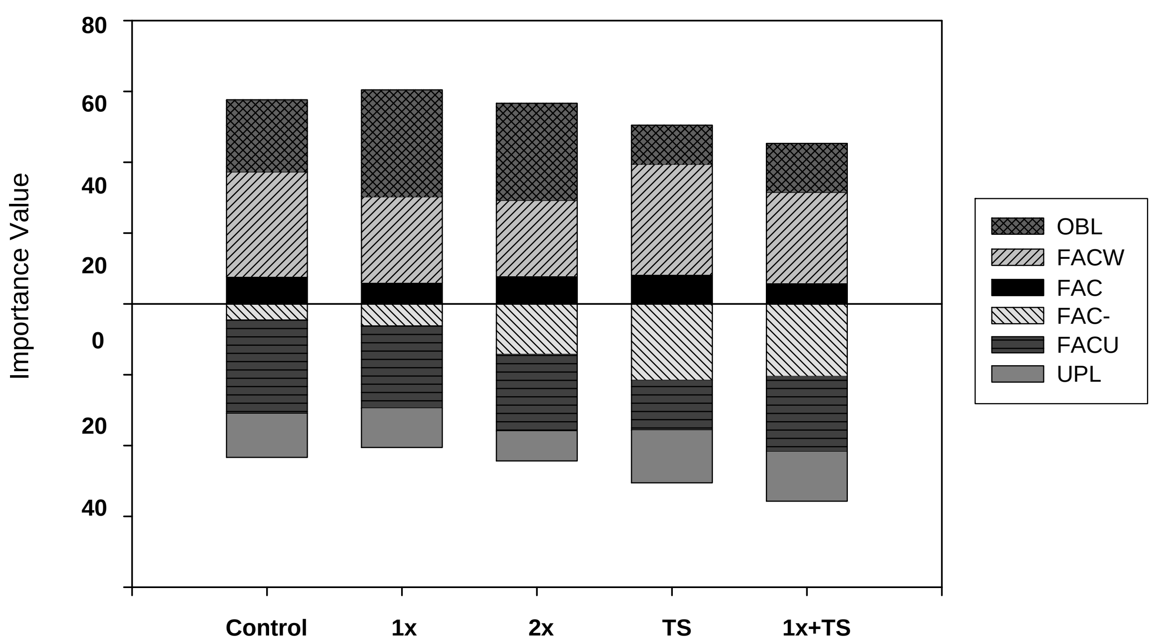
Soil Treatment	Evenness (J')	Shannon Index (H')	Total Species (TS)	Species Richness (SR) ±SE*		Weighted Average (WA) ±SE#	Wetland Indicator
Control	0.822	3.469	68	20.9 ± 0.84	a	2.89 ± 0.35	FAC+
1x	0.852	3.430	56	17.1 ± 1.11	b	2.57 ± 0.18	FACW-
2x	0.845	3.446	59	17.8 ± 1.0	b	2.68 ± 0.57	FAC+
TS	0.772	3.106	56	16.4 ± 0.98	b	2.99 ± 0.43	FAC+
1x+TS	0.775	3.146	58	17.7 ± 0.96	b	3.06 ± 0.14	FAC
				*(p= 0.0136)		#(p= 0.0921)	

In contrast to a study by Brown and Bedford (1997), we found that wetlands with transplanted topsoil had a fewer number of plant species. Our study indicated that TS had the lowest TSP (56) and the control had the highest (68) (Table 10). Rheinhardt (1992) looked at the vegetation at twenty three well developed tidal freshwater wetlands in the lower Chesapeake Bay in Virginia and sixty-nine herbaceous species were found. At WWMS, the lowest number of species were found in the TS and 1x treatments (56) and the highest were found in the control treatment (68) (Table 10).

When Heaven *et al.* (2003) compared the vegetation growing in a created wetland to a natural wetland, they found that 65% of the plants in natural wetlands were OBL while only 34% were OBL in created wetlands. There were also more UPL species in the created wetland as well. In our study, the treatments with compost (1x and 2x) had the largest proportion of OBL species (30 and 27%, respectively) and this proportion is most similar to what Heaven *et al.* (2003) found of created wetlands. The soil treatments with topsoil (TS and 1x+TS) had the lowest proportion of OBL species (11%, and 14%, respectively) and also had the highest proportion of UPL species (15%, and 14%, respectively). From this perspective, the addition of compost during wetland creation was the most helpful in encouraging the presence of OBL species. The addition of topsoil was worse than not adding anything at all (control) for increasing the number of OBL species because it increased the presence of UPL plants and decreased the instance of OBL species (Figure 14). This is likely a result of the topsoil's seed bank introducing upland species to the site. Daniels (2007) personally observed weed species such as *Lespedeza* originate from treatments with topsoil and then spread to the rest of the site in the following seasons. Another factor may be that the treatments containing topsoil had the lowest levels of available P (TS= 5.5 ppm and 1x+TS= 6.5 ppm); and the highest levels of available K and micronutrients (Zn, Mn, Cu, Ca, Mg and Fe; Appendix B).

Overall, the ratios of OBL to FAC: FAC- to UPL were as follows; Control- 57:43, 1x- 60:41, 2x- 56:44, TS- 50:50, and 1x+TS- 45:55. If the jurisdictional wetland criteria were to use the proportions of OBL to FAC and FAC- to UPL, all of these treatments except for the ones containing topsoil (TS and 1x+TS) would pass.

Figure 14. Total Importance Values of general wetland indicator categories for all species in the five different soil treatments at the site. All categories include +/- modifiers. Control= no amendment, 1x= compost at 78 mg/ha, 2x= compost at 156 mg/ha, TS= 15 cm topsoil.



OBL= Obligate Wetland species, FACW= Facultative Wetland species, FAC= Facultative, FAC-=Dry Facultative, FACU= Facultative Upland species, UPL= Upland species. There were no FAC+ species.

3.5 Conclusions

Although the un-amended control had the highest species diversity and species richness of all soil treatments, it did not meet the hydrophytic vegetation criteria set forth by the 1987 manual (Environmental Laboratory 1987). However, the 2x, and TS treatments met the facultative neutral hydrophytic vegetation criteria for USCOE jurisdiction. When using WA's for criteria, all the treatments except for the 1x+TS treatment would be considered hydrophytic. Due to these results, it is recommended that we re-evaluate the vegetative criteria for federal jurisdictional determination for young (< 10 year-old) wetlands. The addition of compost (1x or 2x) produced the highest proportion of OBL species while the addition of topsoil (1x+TS or TS) produced the lowest proportions of OBL and the highest proportions of FAC- and UPL plants. Treatments with topsoil also had the lowest species evenness and diversity, and those with compost were similar to the control which had the highest diversity and evenness, but failed to meet jurisdictional criteria. Due to these findings, we recommend the addition compost soil amendments to soils during wetland creation to increase the amount of wetland species present at the site without compromising species diversity and evenness.

Topsoil treatments had different texture in comparison to the other treatments and also may have input more weed seeds in the seed bank than the other treatments. In this case, an existing seed bank was a disadvantage to the dominance of hydrophytic vegetation, species diversity and evenness.

In future investigations at this site, the effects of microtopography on plant species composition should be investigated. This information would also complement the above-ground tree data (Chapter 4) and root data (Chapter 5) discussed later in this thesis.

4 Influences of Soil Amendments and Microtopography on the Morphological Characteristics of Young *Taxodium distichum* (L.) L.C. Rich. Trees at a Created Tidal Freshwater Swamp in Southeastern Virginia

4.1 Abstract

Changing wetland construction practices to include incorporation of organic matter and restoration of microtopography may improve the establishment and growth of planted woody species. The purpose of this study was to determine the effects of soil amendments (control, 78 Mg/ha compost (1x), 156 Mg/ha compost (2x), 15 cm of topsoil (TS), and 1x+TS); and restored microtopography [level, pit (16.5 cm below level elevation), and mound (11 cm above level elevation)] on previously transplanted *Taxodium distichum* (bald cypress) trees. Morphometrics such as tree height, trunk diameter, basal trunk swelling, crown diameter and branch count were measured three times from December 2005 to October 2006 at a created wetland in Charles City County, Virginia. Overall, soil amendment had little effect on above-ground morphology, but basal trunk swelling was affected ($p = 0.018$) on the last data collection date. Basal swelling was largest for trees growing in the topsoil treatments (TS and 1x+TS). Microtopography treatments strongly affected tree height ($p = 0.033$, 0.055, and 0.003), trunk diameter at 10 cm ($p < 0.0001$ for all dates) and 30.5 cm above the soil ($p < 0.0001$, $p = 0.002$), and the basal trunk swelling ($p = 0.0004$, and 0.003) at every collection date. In all cases, trees in pits were larger than trees on mounds or on level topography. These findings indicate that creation of shallow pits during wetland construction is more

influential than addition of soil amendments to achieve greater above-ground growth in bald cypress.

Key words: *Taxodium distichum*, wetland creation, tree morphology, C allocation.

4.2 Introduction

Many authors have questioned the notion that created wetlands will function as natural wetlands (Langis *et al.* 1991, Reinartz and Warne 1993, Gibson *et al.* 1994, Shaffer and Ernst 1999, Zedler and Callaway 1999, Stolt *et al.* 2000, Zedler and Callaway 2000, Cole *et al.* 2001, Stolt *et al.* 2001, Zedler *et al.* 2001, Zedler and Kercher 2005). When creating wetlands, the equipment used to excavate soil to lower the elevation compacts the soil, removes topsoil, organic material, seed banks and natural microtopography. Many studies comparing created wetlands with natural wetlands have found that created wetlands often have low soil organic matter (SOM) relative to the levels found in natural wetlands (Langis *et al.* 1991, Shaffer and Ernst 1999). Changing wetland creation practices so that soil organic matter levels and microtopography are restored may improve the development of valuable functions in created wetlands, including tree establishment and growth (Cummings 1999, Whittecar and Daniels 1999, Bergschneider 2005).

Soil organic matter is provided in the form of soil amendments such as mulch, compost, topsoil, hay and other high C materials which provide materials and energy necessary to sustain metabolism within the ecosystem. Additionally, SOM improves water retention of the soil, speeds the development of hydric soils, is a nutrient source, and is a source of seed and plant propagules, and beneficial soil organisms.

The term “microtopography” refers to the natural elevation changes occurring on the soil surface. Microtopography is a common feature in natural wetlands and forests in general (Bruland and Richardson 2005). In nature, microtopography is caused by activities such as the deposit of materials via tidal activity, animals, and tree windthrow. The incorporation of microtopographic features into forested wetlands has been recommended because it creates heterogeneous soil and microclimate conditions for tree colonization and improves plant and animal diversity (Titus 1990, Vivian-Smith 1997, Roy *et al.* 1999, Bruland and Richardson 2005, Pennington and Walters 2006). Mounding creates areas that are higher in elevation and usually above the saturated zone, whereas local depressions/windthrow pits have lower elevations that are usually constantly saturated. Mound areas have higher soil and root temperatures during the growing season and greater nutrient availability than lower elevations (Londo 2001). Mounds also contribute aerated soil volume in the wetland and can increase the rooting depth of seedlings (Londo 2001). These combined factors make mounds favored sites for tree establishment as forested wetlands often have lower productivity than upland areas. For example, Chimner and Hart (1996) found that northern white cedar (*Thuja occidentalis* L.) regeneration in upper peninsula wetlands in Michigan were concentrated on mounds. Indeed, mounding has been used in silviculture since the 18th century to prepare sites for reestablishing trees on wet sites (Londo 2001).

Bald cypress trees are characterized by their ability to prosper in flooded conditions (Burns and Honkala 1990). Reinhardt’s study (1992) of 23 freshwater swamps in Virginia, all the trees except for bald cypress were restricted to growing on mounds. This species is an obligate wetland plant (OBL), which means that it almost always occurs in wetlands (see Table 1). Planted bald cypress seedlings grown in constant flooding initially have reduced stomatal conductance and net photosynthesis rates, but these processes recover within 2-3 weeks (Pezeshki 1991). Megonigal and Day (1992) studied the responses of bald cypress saplings to two different flooding treatments- continuously (CF) and periodically flooded (PF). By the third growing season there was no difference in total biomass between the two treatments, although there were differences between treatments in regards to root: shoot (R: S) ratios. PF trees allocated more C to the roots and developed deeper root systems (R: S high) while CF trees had higher above-ground production (R: S low). The authors discussed that the decrease of R: S ratio in bald cypress was not due to dying/dead roots because few dead roots in the continuously flooded treatment were found. The decrease is due to increased C allocation to above-ground growth.

Bald cypress trees also cope with flooded conditions by developing a buttressed (swollen) trunk. A possible theory behind the cause of buttressing is that soil flooding results in a physiological girdle, and that this would inhibit the downward translocation of oxygen and also cause food and auxins to accumulate at the tree base, which stimulates the localized growth (Kramer and Koslowski 1960). The buttress begins at the soil surface and usually ends where the highest water levels reach. This expansion at the base of the tree and is thought to provide stability, support and strength to trees to prevent uprooting or windthrow from shallow rooting and/or poor anchorage. Indeed the definition of the word “buttress” means to support, reinforce, structure, and strengthen (Dictionary.com 2007).

The objective of this experiment was to determine the effects of reconstructed microtopography and two soil amendments (compost and upland topsoil) on the above-ground morphology of bald cypress in a created tidal freshwater swamp in southeastern Virginia.

4.3 Materials and Methods

4.3.1 Site Description and Application of Treatments

See chapter 2 for a complete site and treatment description.

On April 23, 2004, a range of two to five bald cypress trees were planted within each plot, contractors guaranteed one tree at each pit and mound with the remaining being planted at level elevation. Trees were container-grown (root cone: 5 cm diameter and 15 cm deep) for two years before out-planting at Vanasse Hagen Brustlin's (VHB) nursery in Chesapeake, VA. Seed for the trees came from either the Chickahominy River watershed north of Richmond or North Landing River Watershed in Virginia Beach. Each tree was planted with Osmocote 18-6-12, 7 gram slow-release tablets at the recommended rate (The Scotts Company, LLC, Marysville, OH). No additional fertilizer was applied to individual trees for the remaining duration of the experiment.

4.3.2 Measurements Taken

All bald cypress trees on the study site were identified and tagged December 16-18, 2005. Morphometrics included: height (HT), trunk diameter measured 10 cm from the soil surface (DIA 10), trunk diameter measured 30.5 cm from the soil surface (DIA 30), basal trunk swelling- the difference between trunk diameter at 10 cm and 30.5 cm (D diff), crown branch spread (measured as average between widest and perpendicular direction) (CR DIA), and number of branches originating from trunk (BRANCH) were measured on May 25, 2006; and October 21, 2006. December (first collection date) measurements included all mentioned above except DIA 30 and D diff. The D diff measurement was made to quantify bald cypress basal trunk swelling could be considered the beginning of trunk buttressing, which is an adaptation to flooded conditions.

Total height was measured using a standard meter stick and crown diameter was determined using 1-meter calipers measuring the largest diameter for the crown. Due to the small sizes of the young trees, overall stem diameter was measured at the base of the trunk of the tree 10 cm and 30.5 cm from ground level using micro-calipers.

The experimental design was a completely random 2-way factorial (soil treatment x microtopography). Combinations of treatments at each collection date were tested for normality using the tests for normality (Shapiro-Wilk, Kolmogorov-Smirnov, Cramer-von Mises, and Anderson-Darling) uni-variate procedure in SAS version 9.1 (2007). Very few treatment x above-ground data sets were found to be non-normal and comparisons between normal and non-parametric tests resulted in very similar *p*-values. Kirk (1994) and Sokal & Rohlf (1995) both discuss that the F test is “quite robust” with respect to the normality assumption and after considering all of this, we chose to analyze the measurements with JMP software version 6 (2006) using 2-way ANOVA. Branch count was transformed before analysis by taking the square root of the measurement. For combinations which had a significant overall F- test ($p < 0.05$), the Student t- test at $\alpha = 0.075$ was used subsequently for pairwise mean separations.

4.4 Results and Discussion

4.4.1 Tree Height and Trunk Diameter Measurements

There was little evidence that soil treatments had any effect on tree height ($p = 0.3$ to 0.7) (Table 11). Treatment interactions were also not apparent ($p = 0.8$ to 0.9). However, there was evidence that microtopography treatments affected tree height at each collection date ($p = 0.033$, 0.055, and 0.003). Trees growing in pits (lowest elevation) were taller than trees in other treatments regardless of collection date (Table 12). Rapid height growth is important for trees in wetlands for two reasons: 1) competition with other species for light and 2) staying above total submergence (discussed in sections 1.7.2 and 1.8). When considering that the pit depth was approximately 16.5 cm lower than level elevation, and that the mound treatment was 11 cm above the level treatment (see Figure 5), trees in pits could have responded by growing taller either out of competition with the surrounding species or to prevent complete submergence.

Table 11. *p*-values from 2-way Analysis of Variance for each collection date. HT= tree height, DIA 10= diameter at 10 cm, DIA 30= diameter at 30 cm, D diff= basal trunk swelling.

		P>F		
		Dec '05	May '06	Oct '06
HT (cm)	Soil treatment (ST)	0.493	0.708	0.315
	Microtopography (MI)	**0.033**	**0.055**	**0.003**
	ST x MI	0.752	0.866	0.757
DIA 10 (mm)	Soil treatment (ST)	0.990	0.867	0.479
	Microtopography (MI)	**<.0001**	**<.0001**	**0.001**
	ST x MI	0.714	0.835	0.872
DIA 30 (mm)	Soil treatment (ST)	n/a[#]	0.866	0.774
	Microtopography (MI)	n/a	**<.0001**	**0.002**
	ST x MI	n/a	0.916	0.908
D diff (mm)	Soil treatment (ST)	n/a	0.778	**0.018**
	Microtopography (MI)	n/a	**0.0004**	**0.003**
	ST x MI	n/a	0.266	0.693

[#] n/a = data not available

Table 12. Microtopography mean separations (Main Effects)*
HT= tree height, DIA 10= trunk diameter at 10 cm, DIA 30= trunk diameter at 30 cm, D diff= basal trunk swelling.

	Microtopography	n	Dec '05		May '06		Oct '06	
HT (cm)	Pit	20	116.9	a	128.6	a	150.2	a
	Level	22	103.7	b	114.2	b	127.9	b
	Mound	18	104.0	b	115.3	b	127.9	b
DIA 10 (mm)	Pit	20	30	a	27	a	35	a
	Level	22	17	b	19	b	25	b
	Mound	18	16	b	19	b	25	b
DIA 30 (mm)	Pit	20	n/a#		20	a	25	a
	Level	22	n/a		14	b	18	b
	Mound	18	n/a		15	b	19	b
D diff (mm)	Pit	20	n/a		7	a	10	a
	Level	22	n/a		5	b	7	b
	Mound	18	n/a		4	c	6	b

*Treatment means followed by the same letter are not significantly different at $p \leq 0.075$ by Student's 2-sample t- test.
#n/a= data not available.

Microtopography also affected diameter at 10 cm (DIA 10) ($p < 0.0001$ for all dates), 30 cm (DIA 30) ($p < 0.0001$, and $= 0.002$), and basal swelling (D diff) ($p = 0.0004$, and 0.003) for each data collection date (Table 11). In each case, trees in pits had the largest trunk diameter (DIA 10 and DIA 30) (Table 12). The trunk diameter most closely correlated with total tree biomass, meaning that trees in pits likely had greater overall mass than trees on mounds or level microtopography. D diff correlated to the extent of basal trunk swelling which was occurring with the tree. Basal trunk swelling was largest for trees grown in the pits (Table 12) and this was likely due to the constantly saturated conditions of the pits.

There were no significant interactions between soil amendment and microtopography treatments for any of the diameter measurements (p= 0.3 to 0.9) (Table 11). In most cases, soil treatment did not affect diameter, except for D diff in October (p= 0.018) (Table 11). The TS and 1x+TS treatments had the largest D diff of all the soil treatments, with the control soil treatment having the lowest D diff (Table 13). The finer soil texture of the treatments containing topsoil (Appendix A) may have been the reason that these treatments had larger basal trunk swelling. The topsoil treatments likely held more moisture and stayed saturated for longer because of their finer texture, generating lower redox and subsequent physiological responses.

Table 13. Mean trunk diameter difference (D diff) in mm (Main Effects).*

Soil Trt[#]	n	Oct '06
TS	10	9.4 a
1x+TS	10	8.4 ab
1x	11	7.5 abc
2x	14	7.3 bc
control	16	5.9 c

*Treatment means followed by the same letter are not significantly different at p≤ 0.075 by Student's 2-sample t- test.
#Control= no amendment, 1x= compost at 78 mg/ha, 2x= compost at 156 mg/ha, TS= 15 cm topsoil, and 1x+TS.

A closer look at the pairwise comparison results for tree height and diameter reveals mound and level elevations were not statistically different. This implies that pit microtopography may have generated some other site factor in addition to wetter soils and lower elevation. In addition to competition and avoiding submergence, the pits may have accumulated sediment and organic material via tidal activity and local erosion/sloughing (original pit depth was 20 cm, and 2007 pit depth was 16.5 cm) (Figure 5) whereas the mounds and level elevations would not have been able to trap the organic material as easily. The drier sandy soil conditions within mounds (Figure 5) also would not have retained organic matter as well as the wetter pit conditions. Therefore, trees and other plants growing in pits may have benefited from increased levels of organic material or nutrients in the soil. On the other hand, in a study of 23 well-developed tidal freshwater swamps (Rheinhardt 1992), there were not any significant differences between the amount of organic matter content in pits or mounds. Another possible explanation is that there may have been different species present at the mound and level elevations which were directly competing with the bald cypress growing there for resources, resulting in slower growth compared to trees in pits. Additional observations of soil and nutrient properties and plant species composition affected by microtopography over time would be very helpful in determining if this was the case.

My findings that pit trees had larger diameter and height agree with the findings of Elcan and Pezeshki (2002) who investigated biomass allocation in bald cypress in response to flooding and found a significant increase in the above-ground growth of continuously flooded trees compared to the control. Pit trees in this experiment could be considered "continuously flooded" due to water levels shown in Figure 5. Megonigal and

Day (1992) also found that continuously flooded bald cypress allocated more biomass to the trunk mass after three seasons of flooding. These findings may not be consistent with other tree species. For example, Roy *et al.* (1999), found that the opposite was true for the black spruce (*Picea mariana* (p. Mill.) B.S.P.), which is a facultative wetland plant (FACW-). These trees had greater growth rate, terminal shoot height and diameter growing on mounds as opposed to pits. This was attributed to less saturation and a warmer rooting zone. Bald cypress trees have many specialized morphological and physiological ways to cope with flooded conditions and this may be the reason that black spruce, though still a common wetland plant, showed the opposite response to microtopography.

In their study of twenty-three tidal established freshwater swamps in Virginia, Rheinhardt *et al.* (1992) found that the only tree species that which were not confined to growing on mounds were bald cypress trees. This study demonstrates that pit grown bald cypress have greater above-ground growth than bald cypress growing on mounds or level microtopography.

4.4.2 Tree Crown Diameter and Branch Count

Crown diameter (CR DIA) measures the branch spread of the tree and can influence the amount of light that sub-canopy plants receive. CR DIA was not affected by either soil treatment (p= 0.3 to 0.9) or microtopography p= 0.1 to 0.5) at any collection date (Table 14). There were also no apparent interactions between soil and microtopograpy treatments. At the end of the season, *p*-values were at their lowest (soil, p= 0.4, and microtopography, p= 0.2), which may indicate that crown diameter was increasingly influenced by the treatments as the tree aged, but further data collection is necessary to confirm this as seasonal influences may also have influenced these results.

Branch count is another characteristic of tree morphology and can indicate additional details about canopy structure. Microtopography affected branch count in December (p= 0.045) and October (p= 0.049) (Table 14). Trees growing in pits (lowest elevation) had the highest number of branches and those on level soils had the lowest (Table 15). There was no obvious interaction between soil and microtopography treatments for branch count (p= 0.5 to 0.7). Soil treatment did not affect branch number at any of the collection dates but with increasing tree age, treatments may start having an increased influence on branch count as in crown diameter.

Table 14. *p*-values from 2-way Analysis of Variance for each collection date.* BRANCH= branch count, CRN DIA= crown diameter.

		P>F		
		Dec '05	May '06	Oct '06
BRANCH	Soil treatment (ST)	0.390	0.388	0.083
	Microtopography (MI)	**0.045**	0.590	**0.049**
	ST x MI	0.636	0.729	0.579
CRN DIA (cm)	Soil treatment (ST)	0.867	0.958	0.386
	Microtopography (MI)	0.260	0.542	0.186
	ST x MI	0.712	0.842	0.527

*For the 2-way ANOVA, branch count (BRANCH) data were transformed to square roots before analysis.

Table 15. Mean branch count (BRANCH) (Main Effects).*

Microtopography	n	Dec'05		Oct'06	
Pit	20	15.3	a	24.7	a
Mound	18	13.0	ab	20.8	ab
Level	22	9.3	b	16.7	b

*Treatment means followed by the same letter are not significantly different at $p \leq 0.075$ by Student's 2-sample t- test.
Data were transformed to square roots before statistical analysis.
Untransformed BRANCH means are presented in this table.

4.5 Conclusions

Results from this study indicate that trees growing in pit microtopography (vs. mounds or level elevations) will be larger in terms of height and trunk diameter and perhaps better adapted to wetland conditions. Basal trunk swelling (measured by D diff) for bald cypress trees was expected to be larger for trees growing in the pit microtopography since the soil was constantly saturated (Figure 5). No literature was found stating the age at which bald cypress starts to buttress, but our results indicate that they can initiate this adaptation as early as 4 years old. Soil treatment effects for the later collection date may indicate that soil treatment was beginning to influence measurements as the tree aged. Soil treatments including topsoil (TS and 1x+TS) produced the largest basal trunk swelling and the control soil treatment had the lowest. As these trees age, if there is continued above-ground tree growth at the expense of below-ground growth (see Chap. 5), the tree could become top-heavy and not have enough root/soil proliferation to properly anchor the tree. The initiation of buttressing would be a response to this stress-possibly to aid in supporting the tree.

It is important to note that the lack of initial soil treatment effect may have been due to site preparation methods (section 2.3.1) which took great care to ensure correct hydrology and to avoid compaction (Daniels 2007). A typical non-tidal created wetland would have more compacted soil conditions (root limiting bulk densities in soils range from 1.45 Mg m^{-3} for finer textures to 1.75 Mg m^{-3} for coarse loamy textures (Daniels and Whittecar 2004)) and may not have the hydrologic control we had in this study. The addition of compost or topsoil may have had a greater ameliorative effect under more unfavorable initial site conditions.

In this study, microtopography/elevation had the greatest effect on above-ground growth of young bald cypress. Therefore, in created wetlands of similar soil conditions to WWMS (sandy and low compaction), soil amendments may not be as important for early growth of planted bald cypress as the addition of microtopography (specifically, pits). Above-ground growth of trees in pits was likely influenced by higher soil saturation compared to mounds. Pits may also be a means to trap organic material and sediment, resulting in increased levels of organic material and nutrients.

To further understand the causes of these results, further data collection concerning the microtopography such as plant population data and soil properties is recommended. Excluding plant competition from around the trees via weed exclusion disks may favor tree growth for young trees. By adjacent plant exclusion, we could be determined if level and mound trees had smaller heights and trunk diameters because they were being out-competed by nearby plants or not.

5 Influences of Soil Amendments and Microtopography on Root Characteristics in a Created Tidal Freshwater Swamp in Southeastern Virginia

5.1 Abstract

Very few studies of root growth dynamics in created wetlands have been reported, yet vigorous root growth is vital to wetland plant establishment, soil organic matter accumulation, and general rhizosphere function. Overall effectiveness of created wetlands has frequently been limited by destruction of natural microtopography and a lack of soil organic matter. The purpose of this study was therefore to determine the effects of microtopography and soil amendments on root growth and distribution in a created tidal freshwater swamp. MiniRhizotrons were used to obtain root data on three dates (spring, summer and fall) during the 2006 growing season. Root images were recorded to a depth of 40 cm at the study site in Charles City County, Virginia. The effects of four soil treatments and three microtopography treatments were determined for the following measurements: total and average root length (TRL and ARL, respectively); root count (RC); and diameter (RD).

Microtopography affected TRL ($p< 0.0001$, and $=.049$), ARL ($p= 0.016$), and RC ($p< 0.0001$) on various collection dates. In each significant case, roots growing in mounds had the highest means for all measured parameters, and pits had the lowest. Soil treatment also affected TRL ($p= 0.012$, and 0.020), ARL ($p= 0.035$) and RC ($p= 0.046$, and 0.051) on various collection dates. In all significant cases, treatments without soil amendment (control) had longer root length and counts. Interactions between soil treatments and microtopography were also noted. Root distribution showed obvious decreases in rooting depth and for root length in pits (150 mm). The root length distribution was 50 mm deeper (200 mm) in level treatments compared to pits, and 100 mm deeper (300 mm) in mound treatments when compared to level. These results indicate that the installation of mounds during wetland creation can lead to increased root depth, length and count in tidal freshwater wetlands which will increase below-ground biomass and input of organic material to the ecosystem.

Key Words: wetland creation, root morphology, C allocation.

5.2 Introduction

The study of root growth in wetlands is still in its infancy due to the difficulty of collecting root data in saturated soils with traditional methods such as core sampling, which is very labor intensive, time consuming and destructive (Steinke *et al.* 1996, Baker *et al.* 2001). However, the lack of below-ground data significantly underestimates forest ecosystem activity (Vogt *et al.* 1986, Day and Megonigal 1993, Baker *et al.* 2001).

Roots help prevent soil erosion (Steinke *et al.* 1996), and they contribute as much as 60% of annual SOM (soil organic matter) inputs (Day and Megonigal 1993, Rodgers *et al.* 2004). Fine root dynamics are directly influenced by frequent hydrologic fluctuations, such as in tidal wetlands (Baker *et al.* 2001), and relatively subtle changes in microenvironment (Vogt *et al.* 1993). While fine roots (<1mm diameter) comprise less than 10% of total forest biomass, they can account for 50-75% or more of the total net primary productivity (Vogt *et al.* 1986, Megonigal and Day 1988, Powell and Day 1991, Jones *et al.* 1996). In addition, the proliferation of fine roots is critical to plant establishment and growth since they serve as the primary means for water and nutrient uptake (Farrish 1991). Technological advances such as the MiniRhizotron system have made collecting root data in wetland conditions more feasible. MiniRhizotrons allow the direct observation of roots without destroying the roots and with minimal disturbance to the wetland.

The term *microtopography* refers to the natural elevation changes occurring on the soil surface. Microtopography is a common feature in natural wetlands and forests (Bruland and Richardson 2005). The incorporation of microtopography features into forested wetlands creates heterogeneous soil and microclimate conditions for tree colonization, and improves plant and animal diversity via niche diversification (Titus 1990, Vivian-Smith 1997, Roy *et al.* 1999, Bruland and Richardson 2005, Pennington and Walters 2006).

In natural wetlands and forests much of the variation in microtopography is due to windthrow which creates directly adjacent pits and mounds. Mounding creates areas that are higher in elevation and therefore, usually above the saturated zone, whereas local depressions or windthrow pits have lower elevations that are usually constantly saturated. Mounds have greater nutrient availability and higher soil temperature during the growing season (Londo 2001). Mounds also contribute aerated soil volume and can increase the rooting depth of seedlings (Londo 2001). Mounding sites also increases litter decomposition rates due to more optimal conditions for heterotrophic decomposers. These factors make mounds favored sites for tree establishment as forested wetlands often have lower productivity than upland areas.

Many studies comparing created wetlands with natural wetlands have found that created wetlands often have low SOM relative to the levels found in natural wetlands

(Langis *et al.* 1991, Shaffer and Ernst 1999). Soil organic matter is provided in the form of soil amendments such as mulch, compost, topsoil, hay and other high C materials which provide materials and energy necessary to sustain metabolism within the ecosystem. Additionally, SOM improves water retention of the soil, speeds the development of hydric soils, is a nutrient source, and is a source of seed and plant propagules, and beneficial soil organisms.

The plots in this trial were designed to study the main effects and interactions of recreated microtopography and soil treatments on root growth in a created tidal freshwater swamp in southeastern Virginia. We were particularly interested in learning which treatments yielded the greatest root count and total root length. We also wanted to see if there were differences in root length distribution down the soil profile.

5.3 Materials and Methods

5.3.1 Site Description and Application of Treatments

See chapter 2 for a complete site and treatment description. Soil treatment #3 (2x) was not included in this project because there were limited numbers of CAB tubes and we needed to optimize treatment replications. We chose to exclude the 2x treatment because we wanted to further understand the differences between the 1x, 1x+TS, and TS treatments.

5.3.2 CAB Tube Preparation and Installation

On February 24, 2006, clear 5 cm diameter and 0.91 m long CAB (Cellulose Acetate Butyrate) tubes (Bartz Technology, Santa Barbara, CA) were installed into 0.61

m deep hand augured holes at a 45 degree angle relative to the soil surface, 0.30 m away from the northeastern side of the planted bald cypress trunk in pits, mounds and the nearest available level planted cypress (Figure 15 and Figure 16). In order to ease the installation, well point tips were attached to the ends of the tubes before installation with silicon glue and reinforced with a nail (Figure 17). Due to the periodically flooded nature of the research site, 0.30 m of CAB tube remained above-ground. These above-ground sections were painted black and then covered with white paint (Figure 17) (Krylon Fusion for Plastic, Cleveland, OH) to prevent light and heat from influencing root growth and algae proliferation. All tubes were sealed with #11 rubber stoppers (Fisher Scientific) so that on the occasion of higher water levels, water would not leak into them.

To stabilize and anchor the tubes, 1.59 cm diameter rebar was cut into 1.22 m lengths and driven in along the underside of the CAB tubes; it was attached to the top of the CAB tube using hose clamp (Figure 15 and Figure 16). This stabilized the tubes and prevented the presumably buoyant tubes from being pushed out of the ground from the pulsing tidal hydrology of the wetland (Figure 16).

Figure 15: Diagram of the CAB tube installation. Note: Observation tubes were also installed within each plot at the nearest cypress tree with level (flat) microtopography. Figure by author.

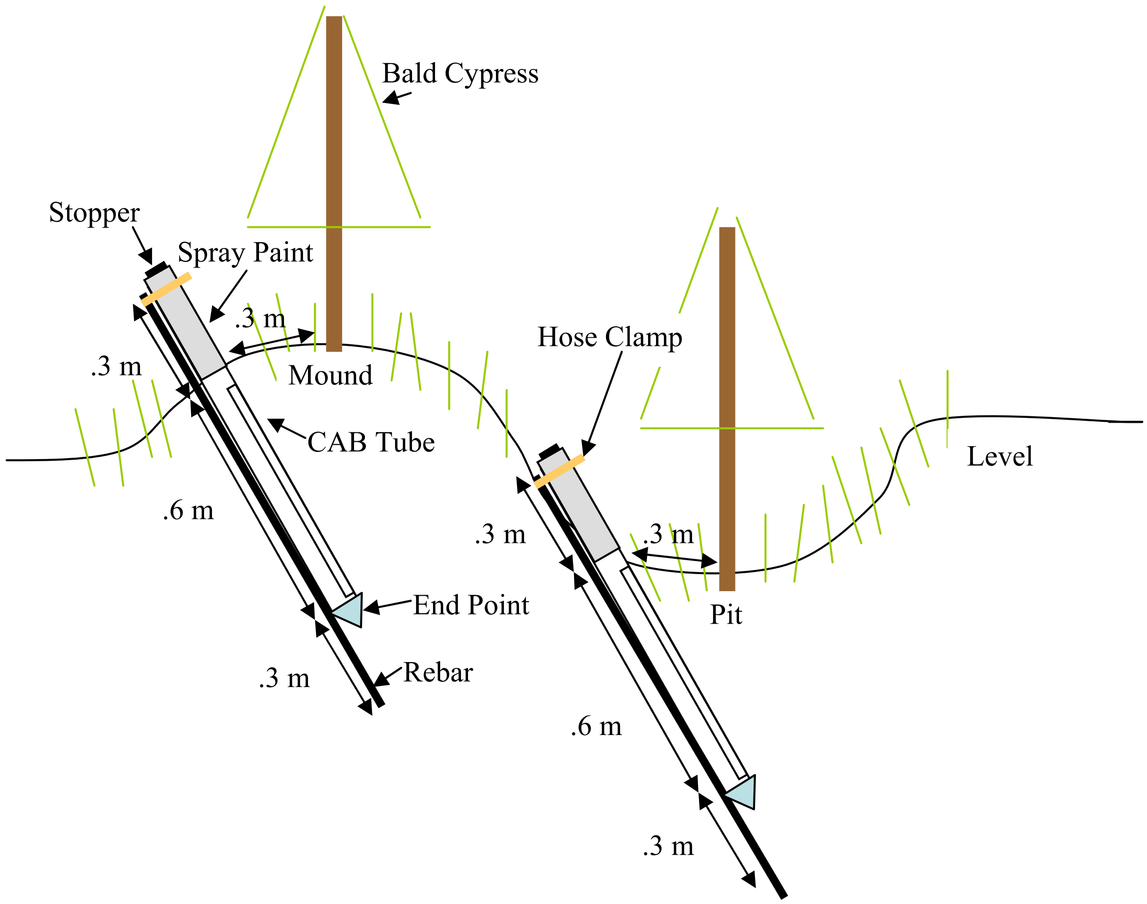
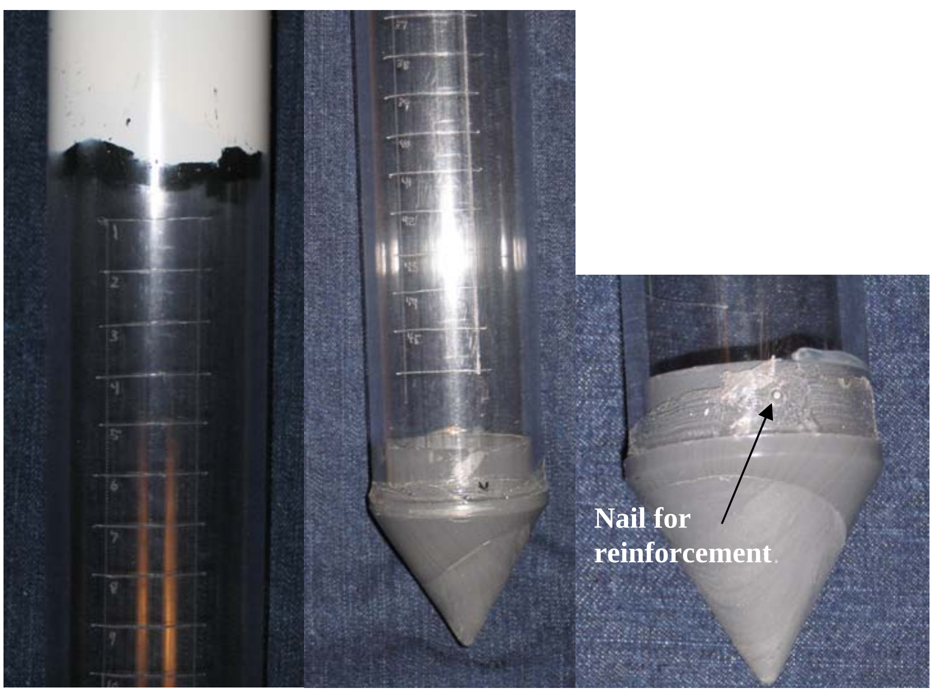


Figure 16. Photograph of an installed CAB tube, February 24, 2006. Photograph by author.

Figure 17. Pictures of CAB tubes. Left to right: the top of a finished CAB tube, the bottom of a finished CAB tube, and detail on the end tip. Photographs by author.



5.3.3 Data Collection and Analysis

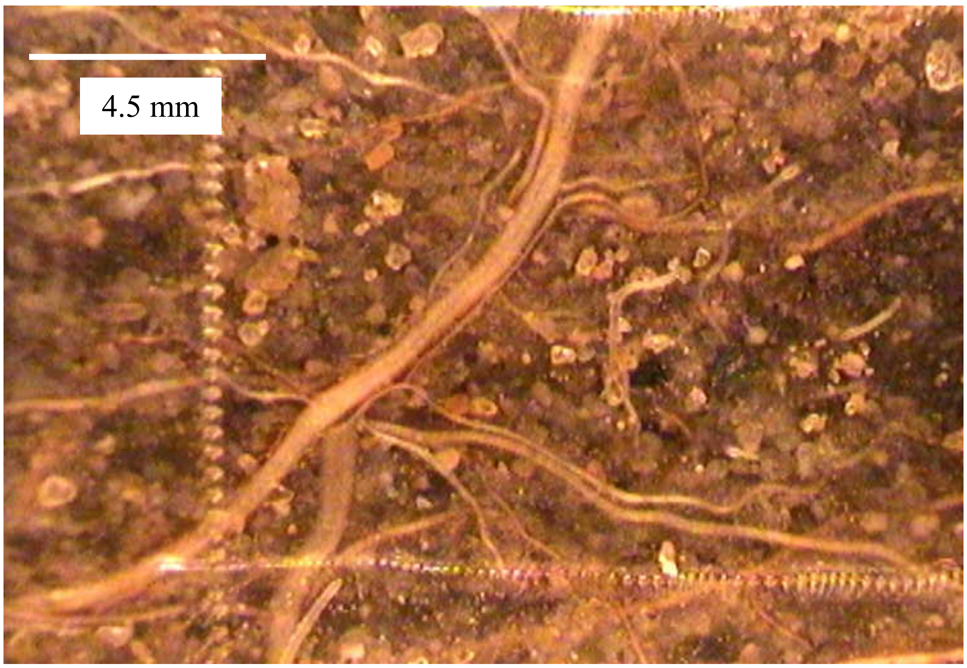
Three to four replications of each combination of four soil treatments and three microtopography treatments totaling 39 tubes were utilized for root measurements (see Table 16).

Table 16. Number of tubes used for each combination of soil and microtopography treatments.

Number of Tubes used for MiniRhizotron Experiment					
		Microtopography			Total
		Pit	Mound	Level	
Soil Treatment	Control	4	4	4	12
	1x Compost	3	3	3	9
	1x Compost + Topsoil	3	3	3	9
	Topsoil	3	3	3	9
					39

Root data were collected from each tube three times during the 2006 growing season (May 17, 2006; July 12, 2006; and September 16, 2006) using the BTC I-CAP Image Capture System (Bartz Technology, Santa Barbara, CA)**.** An indexing handle (Bartz Technology) was used to facilitate data collection. This indexing system moves the camera at set intervals so that the camera may return to exact locations for each data collection at each data collecting session. Forty pictures (Figure 18) were taken in sequence by pulling the camera up from the bottom of the tube at set intervals of 14 mm per picture totaling 56 cm of data for each tube (vertical depth= 10 mm per picture and 40 cm for each tube). See Appendix C for more MiniRhizotron pictures.

Figure 18. Picture of roots taken with MiniRhizotron camera (13x18mm). The vertical and horizontal beaded lines were physical inscriptions that were not utilized for data analysis. Photograph by author.



Pictures were then analyzed using the Root Fly program (Birchfield *et al.* 2006). Root length, diameter and number were recorded. If a root was branched, it received one count for the main root and one for each branch. If roots grew across margins, the root was counted for any horizon where it was observed (Steinke *et al.* 1996). From this information, the means of total root length for the entire tube (TRL), average root length per picture (ARL), total root count for the entire tube (RC) and root diameter for the entire tube (RD) could be determined for soil and microtopography treatments.

The experimental design was a completely random 2-way factorial (soil treatment x microtopography). Combinations of treatments at each collection date were tested for normality using the tests for normality (Shapiro-Wilk, Kolmogorov-Smirnov, Cramer-von Mises, and Anderson-Darling) uni-variate procedure in SAS version 9.1 (2007). Very few treatment x root data sets were found to be non-normal and comparisons between normal and non-parametric (Wilcoxon) tests resulted in very similar *p*-values. Kirk (1994) and Sokal & Rohlf (1995) both discuss that the F test is "quite robust" with respect to the normality assumption and after considering all of this, we chose to analyze the measurements with JMP software version 6 (2006) using 2-way ANOVA. Root count was transformed before analysis by taking the square root. For combinations which had a significant overall F-test ($p < 0.05$), the Student t- test at $\alpha = .075$ was subsequently used for pairwise mean separations.

5.4 Results and Discussion

5.4.1 Total Root Length, Average Root Length and Root Count

Among microtopography treatments, mounds had the highest mean total root length (TRL) at each collection date, although treatment effects decreased as the season progressed (p, 0.0001, = 0.049, and 0.176) (Table 17, and Table 18). There were no significant differences due to soil treatments in May ($p = 0.6$ to 0.9), but differences became more evident as the season progressed ($p = 0.01$ to 0.05) (Table 17). Among soil treatments, the control soil treatment had the highest TRL, and treatments with the lowest values contained topsoil (Table 19). The fine soil texture of the treatments containing topsoil (Appendix A) may be the reason that these treatments produced lower means.

Topsoil had the lowest levels of available P (TS= 5.5 ppm and 1x+TS= 6.5 ppm) and the highest levels of available K and micronutrients (Zn, Mn, Cu, Ca, Mg and Fe; Appendix B). Plants growing in topsoil may not have allocated as much C to below-ground growth because of the increased levels of nutrients and SOM, while control treatment plants (no soil amendments) allocated more C to below-ground growth to obtain the appropriate amount of nutrients.

Table 17. *p*-values from 2-way Analysis of Variance for each collection date. TRL= mean total root length, ARL= mean average root length per window, RD= mean root diameter, RC= mean root count.*

		P>F		
		May '06	July '06	Sept. '06
TRL (mm)	Soil treatment (ST)	0.705	**0.012**	**0.020**
	Microtopography (MI)	**<.0001**	**0.049**	0.176
	ST x MI	**0.006**	0.762	0.874
ARL (mm)	Soil treatment (ST)	0.759	**0.035**	0.752
	Microtopography (MI)	0.504	**0.016**	0.506
	ST x MI	0.803	0.620	0.999
RD (mm)	Soil treatment (ST)	0.988	0.348	0.654
	Microtopography (MI)	0.103	0.078	0.585
	ST x MI	0.844	0.697	0.992
RC	Soil treatment (ST)	0.653	**0.046**	**0.051**
	Microtopography (MI)	**<.0001**	0.142	0.241
	ST x MI	**0.003**	0.784	0.899

*For the 2-way ANOVA, root count data were transformed to square roots.

Table 18. Microtopography Mean Separations (Main Effects).*#
TRL= mean total root length, ARL= mean average root length per window.

	Microtopography	July '06	
TRL (mm)	Mound	1448.14	a
	Level	1058.22	ab
	Pit	935.67	b
ARL (mm)	Mound	4.68	a
	Level	4.58	a
	Pit	3.96	b

*Treatment means followed by the same letter are not significantly different at p≤ 0.075 by Student's 2-sample t- test.
May '06 TRL and RC are in the interaction plots- Figure 19 and Figure 20.

Table 19. Soil Treatment Mean Separations (Main Effects).* TRL= mean total root length, ARL=mean average root length per window, RC= mean root count. 1x = compost at 78 Mg/ha, TS= 15 cm of topsoil, 1x+TS= compost and topsoil combined, control= no amendment.

	Soil Treatment	July '06		Sept '06	
TRL (mm)	Control	1523.02	a	3879.18	a
	1x	1244.47	ab	2555.76	b
	TS	903.09	b	2245.83	b
	1x+TS	793.55	b	2120.62	b
ARL (mm)	Control	4.67	a		
	TS	4.57	ab		
	1x	4.20	bc		
	1x+TS	3.98	c		
RC (mm)	Control	17.37	a	30.21	a
	1x	16.77	a	24.36	b
	TS	14.09	b	23.72	b
	1x+TS	14.03	b	22.90	b

*Treatment means followed by the same letter are not significantly different at p≤ 0.075 by Student's 2-sample t- test.

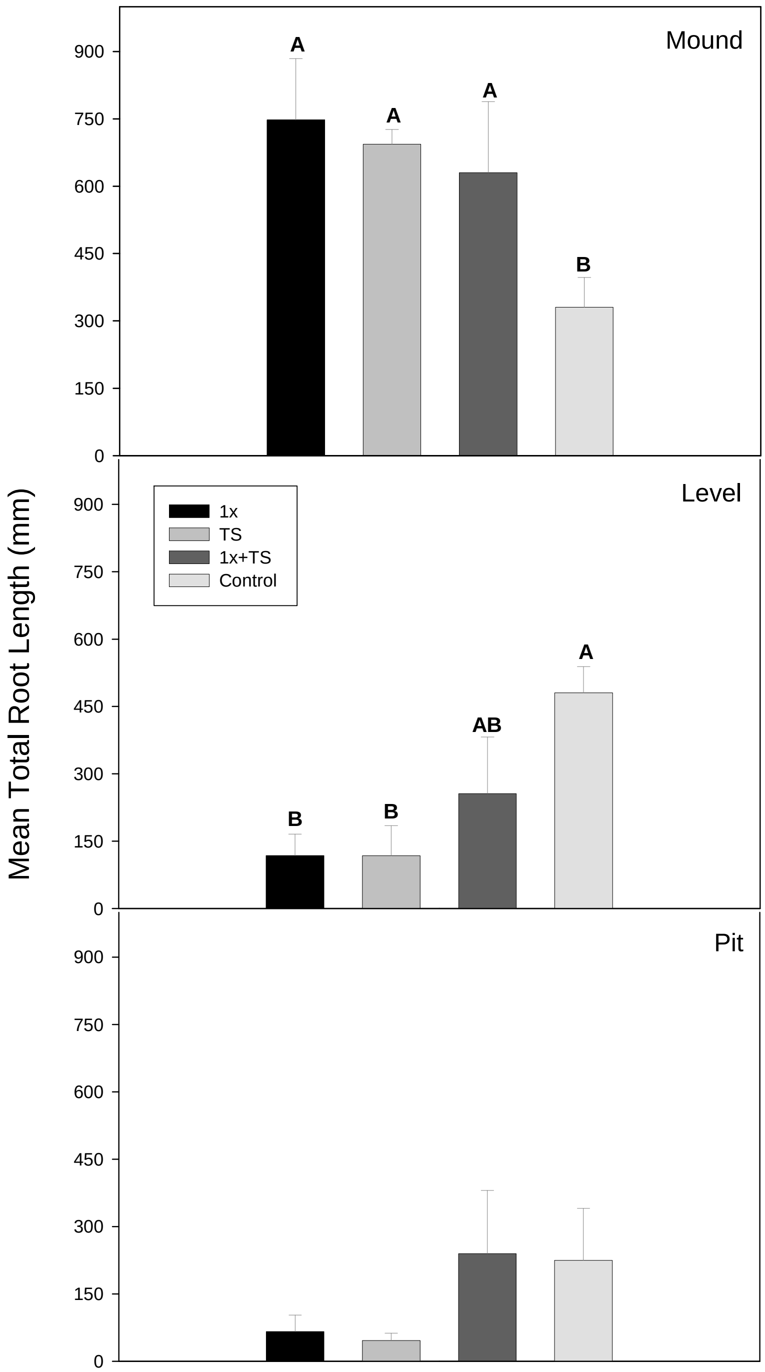
An interaction between soil treatment and microtopography ($p= 0.0006$) for TRL occurred on May 17 (Table 17 and Figure 19). For mound microtopography, 1x, TS and 1x+TS had the longest mean TRL and control had the shortest. At level microtopography, the control soil treatment had the longest TRL while the 1x and TS treatments produced the shortest TRL (the opposite trend). This illustrates that early in the season, plots with soil amendments had higher root length at higher elevations, while at the level elevation the plots with no amendment had more root length.

The mean average root length per window (ARL) was affected by both microtopography and soil treatment on July 12 (Table 17). Soil treatment and microtopography interactions for ARL were not present on any of the dates. The mound and level microtopography had higher ARL than the pit. The control and TS soil treatments had higher ARL than 1x and 1x+TS (lowest ARL) (Table 19).

On May 17, mean root count (RC) among microtopography treatments was significantly different ($p< 0.0001$) with mounds having the highest RC (Table 17, and Table 18). As the season progressed, this relationship weakened (increased *p*-values). On both July 12 and September 16, soil treatment affected RC (Table 17). Control soil treatment had the highest RC and treatments containing TS had the lowest RC (Table 19). For RC on July 12, 1x was not separated from the control while on September 16, it was.

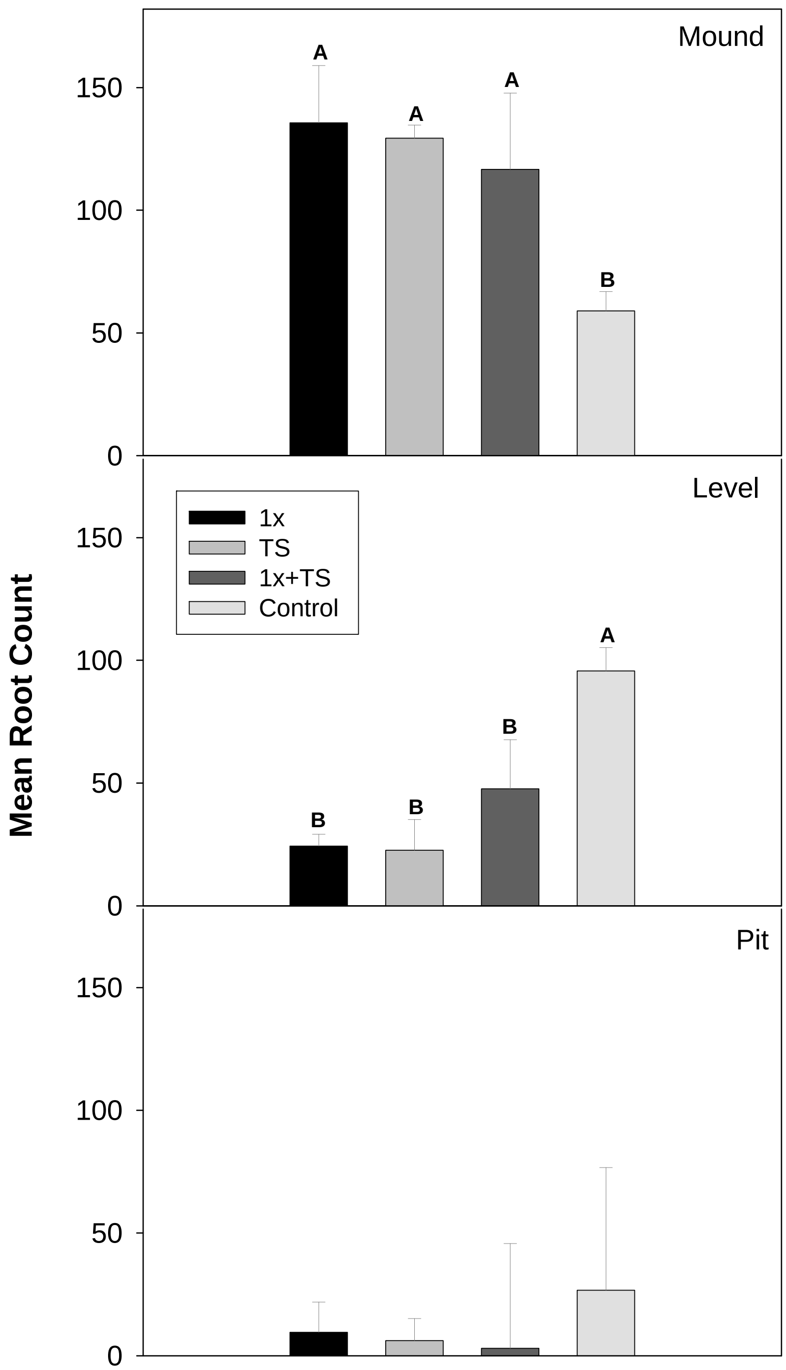
Interactions occurred among soil treatments x microtopography ($p=.003$) for RC on May 17 (Table 17; and Figure 20). For mound microtopography, control soil treatments produced the lowest mean RC and the other soil treatments were higher. At level microtopography, however, the control soil treatment had the highest RC and other soil treatments produced the lowest RC.

Figure 19. Mean total root length interactions between microtopography and soil treatments on May 17. 1x = compost at 78 Mg/ha, TS= 15 cm of topsoil, 1x+TS= compost and topsoil combined, control= no amendment. Bars above each mean indicate standard errors.



Treatment means labeled with the same letter are not significantly different at p≤ 0.075 by Student's 2-sample t- test. n=3 for all treatments except those with the control soil treatment, n=4.

Figure 20. Mean root count interactions between microtopography and soil treatments on May 17. 1x = compost at 78 Mg/ha, TS= 15 cm of topsoil, 1x+TS= compost and topsoil combined, control= no amendment. Bars above each mean indicate standard errors.



Treatment means labeled with the same letter are not significantly different at p≤ 0.075 by Student's 2-sample t- test. n=3 for all treatments except those with the control soil treatment, n=4.

Previous studies on elevation changes in wetlands and flooding effects on tree growth report similar trends (Megonigal and Day 1988, Megonigal and Day 1992, Baker *et al.* 2001). Megonigal and Day (1992) found that periodically flooded bald cypress had deeper root systems because they allocated more resources to root growth than continuously flooded trees did. Their periodically flooded bald cypress trees were most similar to the mound bald cypress (see water table relative to microtopography elevations in Figure 5) in this trial; therefore, our results are consistent with their findings.

In a study on microtopography and fertilizer effects on root growth in wetland forests, Neatrour *et al.* (2005) found that roots responded to changes in elevation but not the addition of fertilizer. Fine root mass was positively correlated with elevation. In general, roots were least abundant in lower elevations called "hollows". Our study agrees that elevation per se does have the largest impact on rooting, and that the roots respond to aeration over nutrition. The root length and count interaction results from May indicate that addition of organic material only affected root characteristics at the mound elevations. This was probably because at higher elevations, roots develop in nutrient-rich areas while in saturated conditions; they grow close to the soil surface due to lack of oxygen. Neatrour *et al.* (2005) also found a negative relationship between soil nutrient availability and root biomass. Their findings are consistent with the findings in our study in that the control soil treatment had the greatest root length and count, while the treatments with topsoil (which had the highest levels of nutrients) had the lowest.

Rodgers *et al.* (2003) found that although flooding decreases root elongation of individual roots, root density actually increased: therefore, below-ground production remained similar to periodically flooded sites. While our results did show decreased root length due to anaerobic conditions, increases in root count or density were not found.

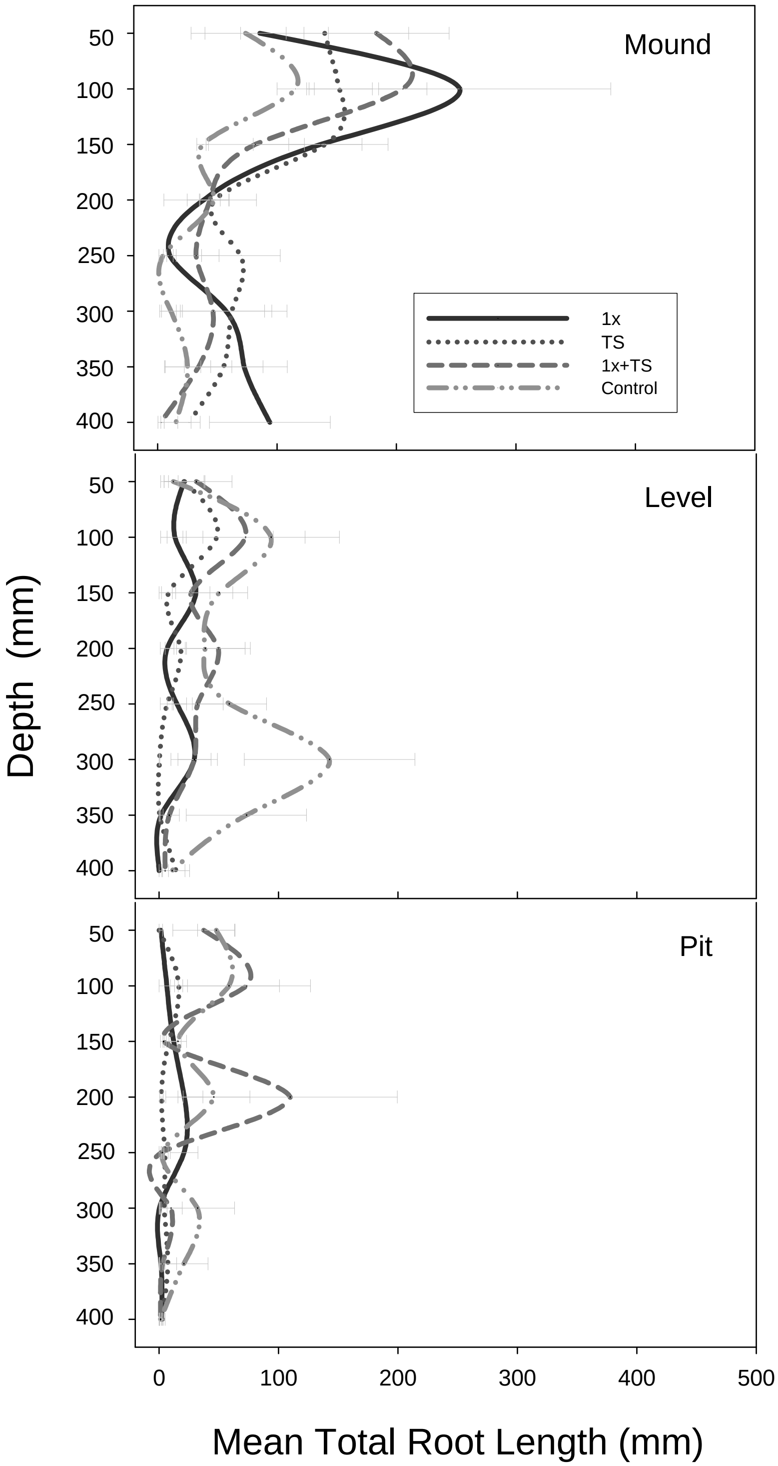
5.4.2 Root Distribution

Root length increased as the season progressed (Figure 21, Figure 22, Figure 23). A bimodal distribution of root length was evident, particularly in mounds on July12 for soil treatments with topsoil, and for both mound and level elevations on September 16. Root length was usually concentrated from 100 to 150 mm deep and also from 250-300 mm deep. This may have been due to differences in species present near the observation tubes since this study did not discriminate among species. Bimodal distribution was also present in pits (1x, 7/12), but observations were at a much lower amplitude. Pit root lengths also were concentrated from 50 to 100 mm and 200 to 250 mm deep.

Mounds with 1x soil treatment had longer overall root lengths within the upper 250-300 mm of the profile for July 12 and September 16 (Figure 22 and Figure 23) than the other soil or microtopography treatment combinations. On July 12 and September 16, the control soil mounds had relatively even root length down to 400 mm. On July 12 and September 16, the topsoil treatments (1x+TS and TS) at all elevations had a somewhat even total root length distribution in comparison to the other two soil treatments (Figure 22 and Figure 23).

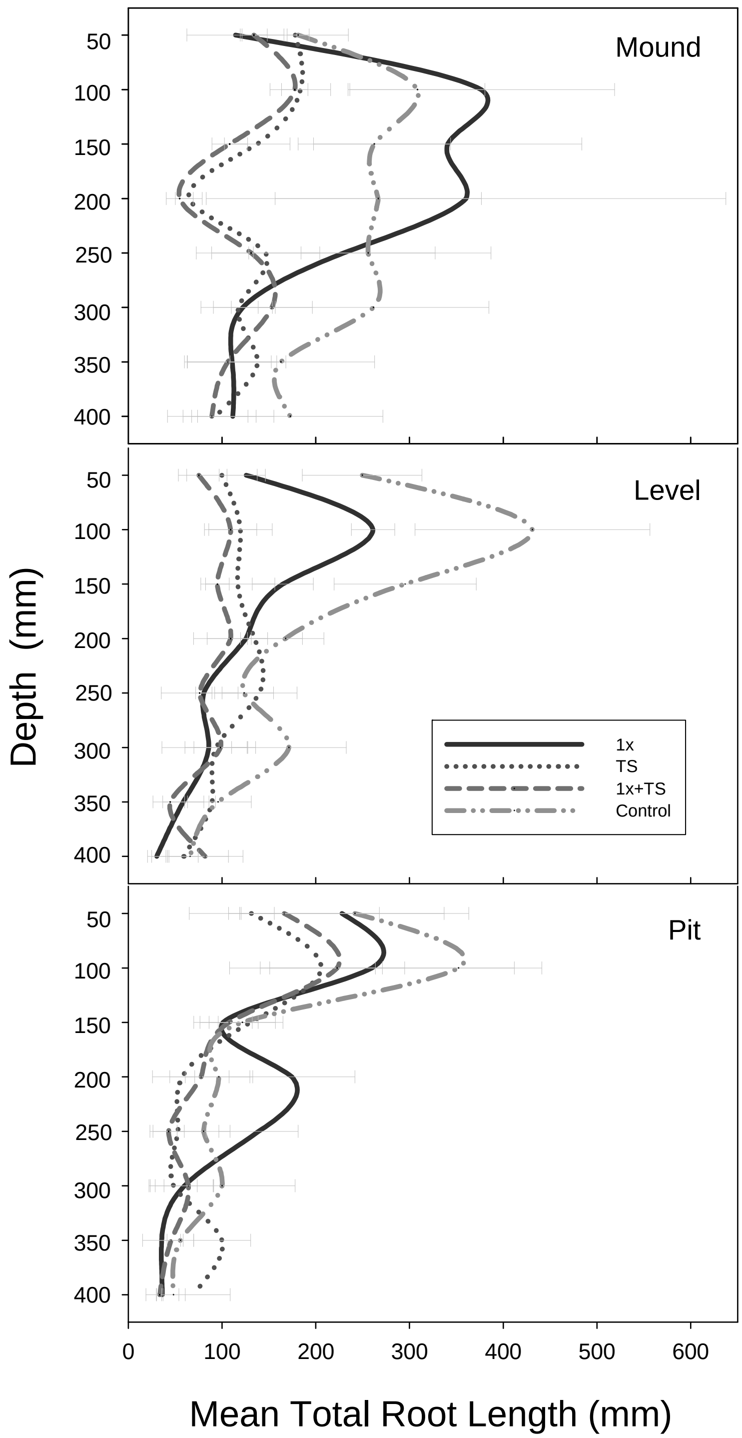
Regardless of season, root distribution generally decreased with depth (Steinke *et al.* 1996). In forested ecosystems, fine roots are most abundant in top 10-30 cm of soil (Burke and Raynal 1994, Mou *et al.* 1995, Hendrick and Pregitzer 1996, Rytter and Hansson 1996), especially in forested wetlands (Lugo *et al.* 1988, Jones *et al.* 1996, Rodgers *et al.* 2004). For July 12 and September 16, the combination of 1x with mound and 1x+TS with pit, reconfirmed previously stated trends with decreases starting around 250-300 mm deep (Figure 22 and Figure 23). Pit roots showed obvious decreases at all dates around 100-150 mm which was shallower in the profile than level (150-200 mm) and mound (250-300 mm).

Figure 21. May 2006 mean root density (total root length depth distribution) for each microtopography by soil treatment (with SE). 1x = compost at 78 Mg/ha, TS= 15 cm of topsoil, 1x+TS= compost and topsoil combined, control= no amendment. Bars shown by depth are standard errors.



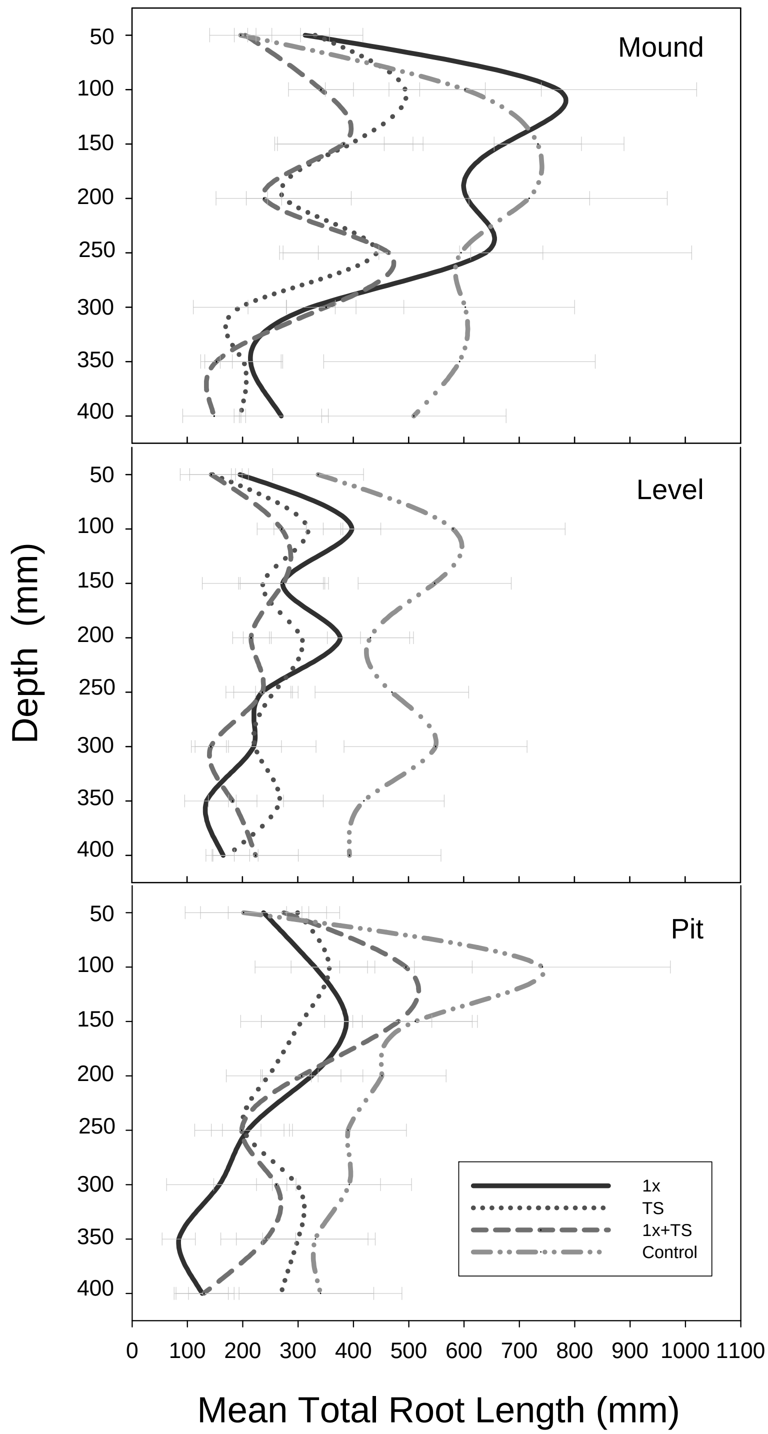
n=3 for all treatments except those with the control soil treatment, n=4.

Figure 22. July 2006 mean root density (total root length depth distribution) for each microtopography by soil treatment (with SE). 1x = compost at 78 Mg/ha, TS= 15 cm of topsoil, 1x+TS= compost and topsoil combined, control= no amendment. Bars shown by depth are standard errors.



n=3 for all treatments except those with the control soil treatment, n=4.

Figure 23. September 2006 mean root density (total root length depth distribution) for each microtopography by soil treatment (with SE). 1x = compost at 78 Mg/ha, TS= 15 cm of topsoil, 1x+TS= compost and topsoil combined, control= no amendment. Bars shown by depth are standard errors.



n=3 for all treatments except those with the control soil treatment, n=4.

5.5 Conclusions

Overall, the microtopography treatments had greatest effect on root measurements. Roots growing in mounds had the highest means for all measured significant parameters, and pits had the lowest means. When considering these results along with those of Chapter 4, the higher root growth found in mounds in this study suggests a shift of C allocation from above-ground to below-ground growth (since shoot growth was greater for pit microtopography than for mound). Other studies (Powell and Day 1991, Day and Megonigal 1993) also report that during flooding, less C is allocated below-ground while sites with less flooding allocate more C to below-ground growth. From this study, we see that adding mounds to the soil surface during wetland creation increased total root count and length in the wetland which would presumably increase below-ground productivity and contribute to site SOM accumulation.

Treatments without soil amendment had longer roots and counts, but this effect was minor in comparison to microtopography. The exclusion of soil amendments is not recommended due to its contribution of weedy competitive plants (Chapter 3) and because it is likely that there was increased root growth in the control plots in order to obtain adequate nutrients. In addition, the interactions showed that in mounds, the 1x treatment had higher root counts and length while in pits; the control produced the highest root length and count. Therefore, in some circumstances, adding 1x compost to mounds will result in more root growth.

Root length distribution showed obvious decreases in rooting depth for the majority of roots in pits (150 mm). As elevation increased to level and mound microtopography, the majority of the roots penetrated 50 mm deeper from pit to level

(200 mm), and 100 mm from level to mound (300 mm). The root distribution changed due to elevation because the degree of water saturation decreased as the elevation increased. Treatments with topsoil had a more even root distribution regardless of elevation in comparison to other soil treatments.

6 Overall Conclusions and Recommendations

None of the treatments applied in this study produced a vegetative community that met the traditional US Army Corps of Engineers criteria for jurisdictional determination which only considers dominant species. However, when using the same criteria with all species present, the control, 1x and 2x soil treatments had a > 50% ratio of obligate wetland to facultative plant species and therefore would have met vegetative criteria. The addition of compost (1x or 2x) produced the highest proportion of obligate wetland species present (30%, and 27%, respectively). In contrast, addition of topsoil (1x+TS or TS) led to the lowest proportions of obligate wetland species (11%, and 13%, respectively) and the highest proportions of upland plants. Topsoil may have introduced more weed and upland seeds from its seed bank to the site. In this case, the introduced soil seed bank appeared to be a disadvantage to the dominance of hydrophytic vegetation, species diversity and evenness. From these results, it is not recommended to add topsoil from upland locations during wetland creation, and soil salvaged from wetland impact sites would be a better option.

Overall, the control soil treatment provided the highest plant species diversity and species richness of all soil treatments. Treatments with topsoil had the lowest species evenness and diversity. When considering these results, the addition of compost soil amendments to soils during wetland creation is recommended to increase the amount of wetland species present at the site without compromising species diversity and evenness. It is also recommended that we re-evaluate the vegetative criteria for a jurisdictional wetland for young wetlands.

Adding pits during wetland creation increased bald cypress height and trunk diameters, apparently at the cost of below-ground production, which could be problematic as the trees grow larger. The increased development of basal trunk swelling, an adaptation to flooding, was also largest in pits and could provide support and stability to these top-heavy trees in the future as they become buttressed. The addition of mounds increased root length and count in the recreated wetland soils. Therefore, the addition of microtopography positively influences wetland vegetative functions.

Soil treatments did not have as much of an effect on the above-ground characteristics of bald cypress as microtopography did. For the last sampled date, soil treatments with topsoil had greater basal trunk swelling than the other soil treatments. The below-ground rooting characteristics were affected by soil treatment in July and September. The control soil treatment (no amendment) had the greatest root length and count and this was most likely due to of the lack of organic material and nutrients present requiring greater root development in order for the plants to obtain adequate resources. Treatments with topsoil produced the lowest root length and counts. Increased soil moisture due to finer texture combined with higher levels of nutrients probably did not require extended root growth to obtain adequate moisture and nutrients.

The overall limited effect of soil amendments in comparison to microtopography may be due to the lack of soil compaction in the study site and the fact that appropriate subsoil moisture levels were ensured by tidal control (Daniels 2007). Soil amendments may make more of a difference on above-ground bald cypress characteristic in a typical created wetland sites which have more compacted soils and less hydrologic control than WWMS.

From these studies, I found that both the addition of microtopography and soil amendments in the form of compost are beneficial to the development of different vegetation functions which are important to a tidal freshwater swamp, namely increased root biomass (mounds), increased bald cypress height, diameter and basal trunk swelling (pits), and the growth of hydrophytic vegetation (compost).

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Appendix A. Particle Size Analysis of the plots, collected January 2007. Results are organized by treatment and separated by depth of samples.

Plot	Treatment*	Depth(cm)	Total % Sand	Total % Silt	Total % Clay	Texture Class
5	1	0-3	96	0	4	Sand
7	1	0-3	96	0	4	Sand
9	1	0-3	93	0	7	Sand
17	1	0-3	97	0	3	Sand
20	1	0-3	97	0	3	Sand
5	1	20-25	96	4	0	Sand
7	1	20-25	98	0	2	Sand
9	1	20-25	96	0	4	Sand
17	1	20-25	98	0	2	Sand
20	1	20-25	98	0	2	Sand
3	2	0-3	94	0	6	Sand
11	2	0-3	96	0	4	Sand
14	2	0-3	95	1	4	Sand
16	2	0-3	96	0	4	Sand
3	2	20-25	97	1	2	Sand
11	2	20-25	98	0	2	Sand
14	2	20-25	98	0	2	Sand
16	2	20-25	97	1	2	Sand
1	3	0-3	96	0	4	Sand
6	3	0-3	97	0	3	Sand
10	3	0-3	96	0	4	Sand
21	3	0-3	98	0	2	Sand
1	3	20-25	93	1	6	Sand
6	3	20-25	98	0	2	Sand
10	3	20-25	96	0	4	Sand
21	3	20-25	97	0	3	Sand
2	4	0-3	50	31	19	Loam
12	4	0-3	48	30	22	Loam
15	4	0-3	70	14	16	Sandy loam
18	4	0-3	43	34	23	Loam
2	4	20-25	97	0	3	Sand
12	4	20-25	97	0	3	Sand
15	4	20-25	94	0	6	Sand
18	4	20-25	97	0	3	Sand
4	5	0-3	41	37	22	Loam
8	5	0-3	46	32	22	Loam
13	5	0-3	34	37	29	Clay loam
19	5	0-3	48	34	18	Loam
4	5	20-25	97	0	3	Sand
8	5	20-25	89	4	7	Sand
13	5	20-25	98	0	2	Sand
19	5	20-25	96	0	4	Sand

*Treatments: 1) Control; 2) Compost 1x; 3) Compost 2x; 4) Topsoil + 1x Compost; 5) Topsoil only.

Appendix B. Routine analysis of post-treatment soil samples collected in summer 2007.

Averages				mg/kg dilute double acid extractable									% of estimated CEC			
Treatment	**Depth (cm)**	**pH**	**C:N**	**P**	**K**	**Ca**	**Mg**	**Zn**	**Mn**	**Cu**	**Fe**	**B**	**Acidity**	**Ca Sat.**	**Mg Sat.**	**K Sat.**
1	0-3	6.45	8.46	9.20	24.20	397.20	43.60	2.98	9.06	0.82	81.40	0.40	3.80	79.34	14.32	2.44
1	25-30	6.42	2.41	13.60	13.60	172.20	19.60	2.88	9.50	0.66	82.60	0.10	3.08	79.10	14.68	3.12
2	0-3	6.61	9.95	9.00	29.50	530.50	53.50	3.83	18.00	0.83	98.03	0.53	4.48	79.93	13.30	2.28
2	25-30	6.33	2.92	13.00	12.50	178.00	20.25	3.50	9.48	0.85	82.78	0.10	3.30	79.10	14.78	2.85
3	0-3	6.51	8.30	10.75	23.00	375.75	40.75	2.95	14.15	1.10	85.15	0.30	6.47	78.78	13.85	2.55
3	25-30	6.05	6.94	10.75	16.00	245.50	28.00	5.20	18.75	0.93	167.50	0.18	16.83	67.88	13.13	2.20
4	0-3	6.13	10.24	5.50	60.00	671.00	81.00	2.73	31.01	3.28	151.05	0.30	13.03	69.95	13.80	3.25
4	25-30	5.90	3.91	19.25	16.25	158.50	23.25	3.55	23.20	0.95	182.35	0.10	15.18	65.58	15.88	3.43
5	0-3	6.25	9.86	6.50	55.75	793.00	101.50	2.45	44.10	2.03	114.68	0.40	13.58	69.08	14.80	2.53
5	25-30	6.37	6.32	9.25	16.50	196.50	27.50	3.75	18.28	1.03	179.15	0.13	26.55	67.55	16.43	2.75

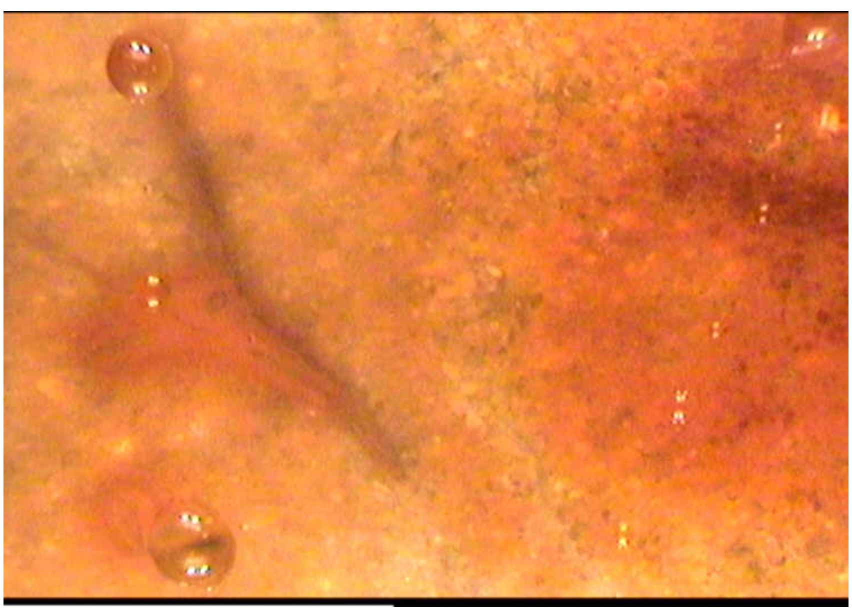
** Treatments: 1) Control, 2) 1x, 3) 2x, 4) 1x+TS, 5) TS

Appendix C. MiniRhizotron photographs. All photographs by author.

These two pictures illustrate changes which occurred between the 2nd and 3rd data collection dates for the 1x+TS-Mound treatment at a depth of 360 mm.

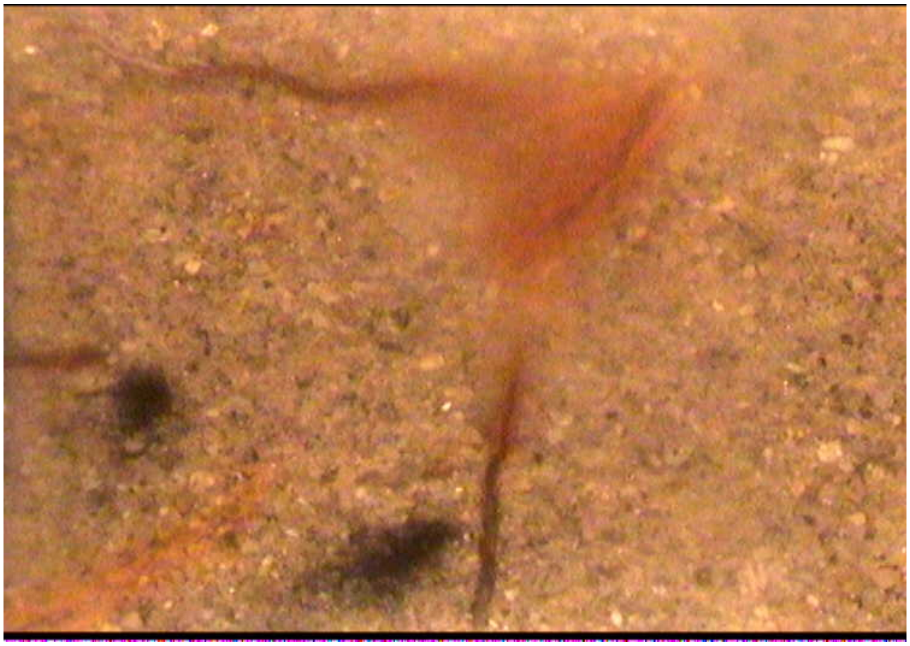
July 12, 2006

September 16, 2006



These two pictures illustrate changes which occurred between the 2nd and 3rd data collection dates for the TS-Level treatment at a depth of 320 mm.

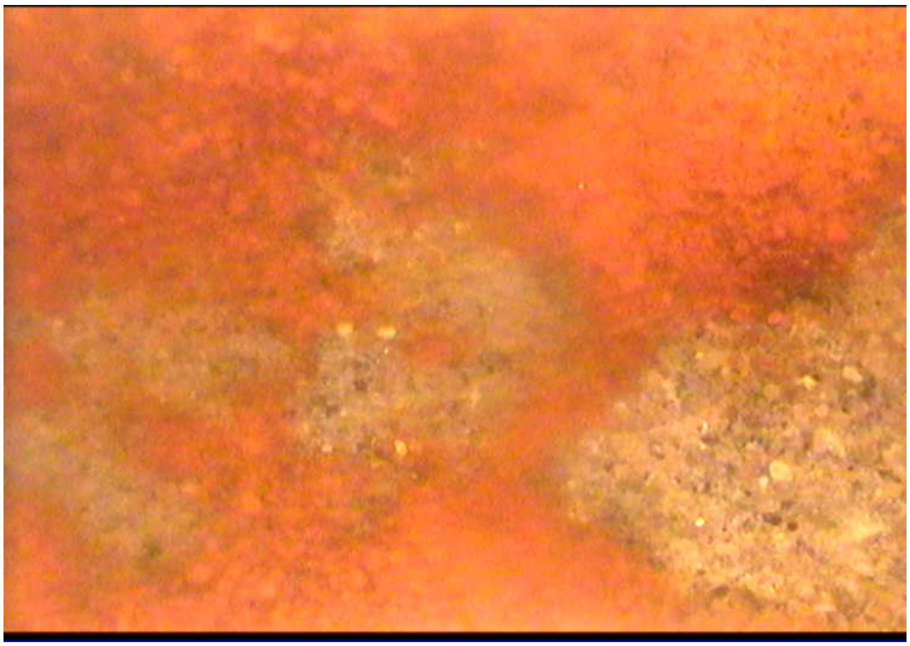
July 12, 2006



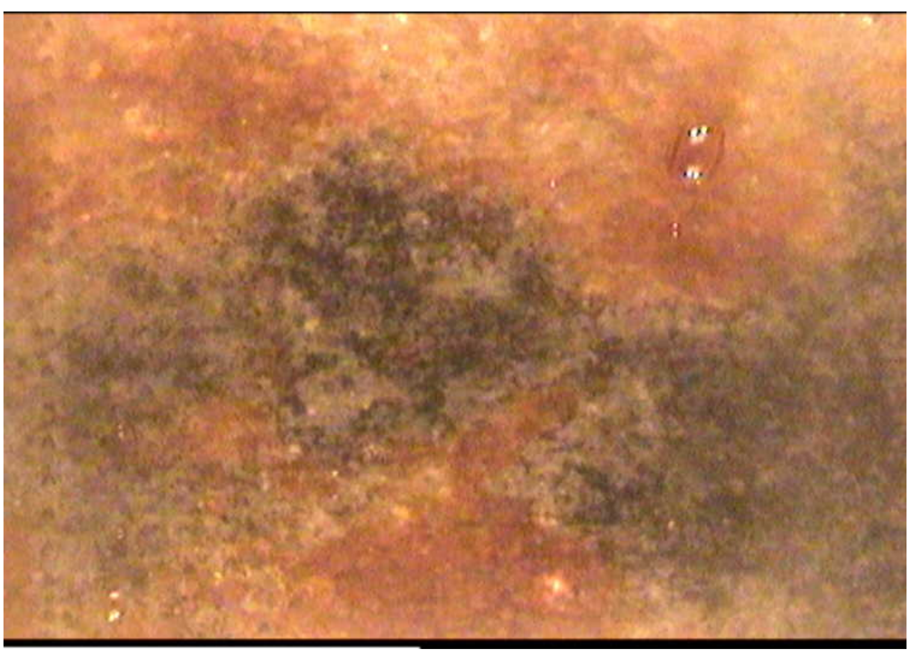
September 16, 2006

These two pictures illustrate changes which occurred between the 2nd and 3rd data collection dates for the Control-Pit treatment at a depth of 270 mm.

July 12, 2006



September 16, 2007

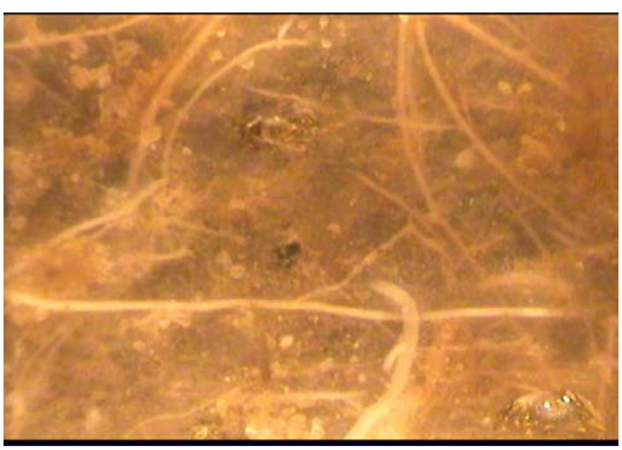


These three pictures show the control soil treatment with each of the three microtopography treatments at very similar depths below local ground surface on July 12, 2006.

Mound, Depth: 140 mm

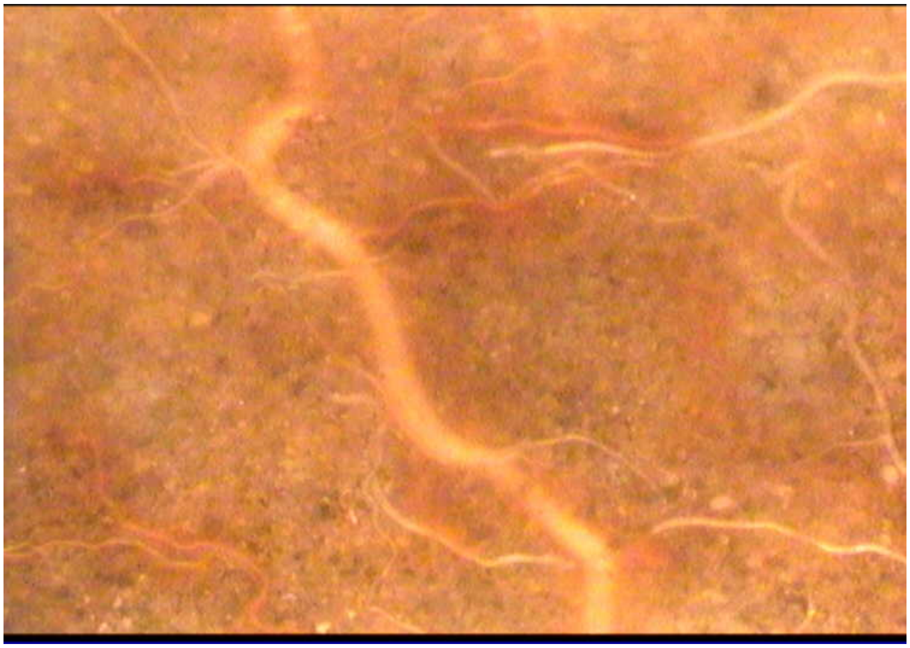
Pit, Depth: 60 mm

Level, Depth: 70 mm



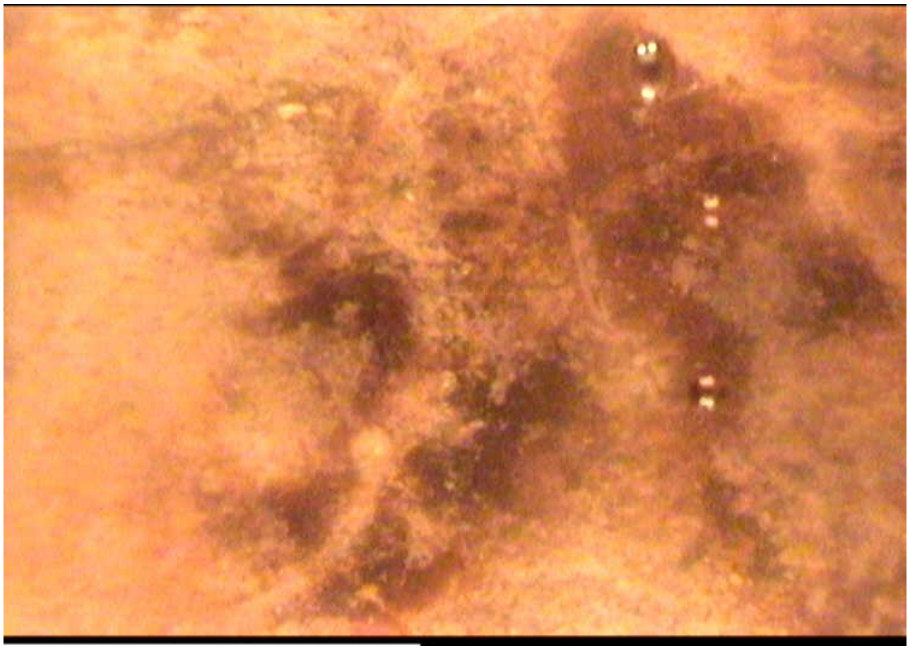
Additional root pictures of interest.

Treatment: 1x-Mound Depth: 230 mm Date: July 12, 2006



Treatment: Topsoil-Mound Depth: 110 mm Date: May 17, 2006

Treatment: 1x+TS-Mound Depth: 90 mm Date: September 16, 2006



Treatment: 1x+TS-Pit Depth: 130mm Date: September 16, 2006

Vita

Sarah Dickinson received her B.S in Botany with concentrations in “Plant Physiology & Molecular Biology”, and “Botanic Gardens & Conservatories” from Michigan State University (MSU) in 2002 with honors. After her graduation from MSU, she worked until 2004 in a management position involved in seed and cutting plug production; stock plant management; seed and cutting purchasing; and research at a wholesale perennial nursery in Grand Rapids, MI. She started her M.S. program at Virginia Polytechnic Institute and State University (VT) in January 2005. Sarah’s research interests include wetland creation, restoration and wetland plants. During her stay at VT, she has enjoyed her responsibilities as a teaching assistant for Indoor Plants, Woody Landscape Plants I and Woody Landscape Plants II. During her last semester, she worked as a research assistant for Roger Harris preparing multi-media educational materials for urban foresters- improving tree structure; and nursery growers- Best Management Practices. She defended in the fall of 2007. After her master’s degree, she will continue her work with Roger Harris and Susan Day, and will also assist in the soil subcommittee of the Sustainable Sites Initiative which plans to apply scientific research to establish an industry-adopted mechanism with standards by which sustainable site development is measured. In her free time she enjoys hiking, botanizing, travel, photography, painting and sewing.